

**Stratigraphy, Bathymetry and Synsedimentary Tectonics
of the Early Jurassic of NW Switzerland**

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Gewidmet
Prof. Dr. Andreas Wetzel,
meiner Familie,
meinen Freunden,
Annette

“Eat
The
Elephant”

APC

Abstract

The Early Jurassic full-marine sediments in NW Switzerland accumulated in the slowly subsiding area between the southwestern part of the Swabian Basin and the eastern Paris Basin. These deposits are dominated by fine-grained siliciclastics, but calcarenitic and phosphorite-rich strata are intercalated. Unlike in the adjacent regions of SW Germany and E France, they are arranged in a quite complex stratigraphic architecture characterised by rather abrupt facies changes, erosive truncations and gaps. Despite many common features in NW Switzerland, the sediments are considerably different with deposits of a similar age in SW Germany and E France that the definition of regional lithostratigraphic units is justified constituting the “Staffelegg Formation”. The Staffelegg Formation comprises 11 members and 9 beds. Several of these beds represent distinct correlation horizons. Some of them correspond to strata or erosional unconformities encountered in the Swabian realm, some of them can be correlated with strata in the Paris Basin.

The thickness of the Early Jurassic strata varies between 25 and 70 m. In the eastern and central parts of NW Switzerland, sediments Sinemurian in age constitute about 90% of the thickness. To the West, however, in the Mont Terri area, Pliensbachian and Toarcian deposits form 70% of the thickness. The accommodation space of the Early Jurassic strata was controlled mainly by eustatic sea-level changes. While eustatic sea-level rise was low, isopach maps having a chronostratigraphic resolution of one sub-stage provide clear evidence of differential subsidence as pre-existing faults in the basement that formed

during the late Palaeozoic became reactivated. Orientation of relative thickness anomalies follow the fault trends either those of the Rhenish Lineament or those of the North Swiss Permocarboniferous Trough. Isopach anomalies are superimposed on a general trend of decreasing thickness to the South. Their small areal extension suggests that strike-slip movements occurred locally with a mosaic of basement blocks. Reactivation of faults in the basement during the Early Jurassic is also evidenced by temporally enhanced hydrothermal activity as documented by chronometric age of veins and mineral alterations.

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Introduction

During the Early Jurassic, the study area being located in NW Switzerland and adjacent parts of SW Germany and E France was situated within the southern part of an epicontinental basin that extended over Central Europe (Fig. 1; Ziegler 1990). During the Early Jurassic, subsidence was low, as the enhanced subsidence following a late Palaeozoic tectonic phase decelerated (Fig. 2; Wildi et al. 1989; Loup 1992, 1993; Wetzel et al. 2003). Furthermore during the Triassic, the relief formed during the Variscan orogeny was denudated. Thus this part of the epicontinental basin represented a peneplain at the end of the Triassic as recorded by generally fine-grained deposits (e.g., Bachmann et al. 2008; Jordan 2008). Nonetheless, a major transgression took place that represented the onset of marine conditions that lasted until the Cretaceous (Fig. 3; Ogg et al. 2016). Within this context the Early Jurassic strata within the study area are particular of interest because of several reasons.

1. The shallow marine conditions led to small-scale facies variations and condensed intervals. Over the years, thus, stratigraphic units based on local observations became established and resulted finally in a no longer applicable lithostratigraphic subdivision (Reisdorf et al. 2011). Furthermore the correlation of these units with lithostratigraphic units defined in adjacent areas remained tendentious.
2. Subsidence was low and hence, accommodation space could be severely affected by sea-level changes. To quantify depositional water depth, besides classical considerations based on lithofacies (Allen & Allen 2013), vertebrate fossils have some potential to estimate depositional water depth when taphonomic processes are taken into account. The Early Jurassic strata are very suitable for such a study as they contain numerous more or less complete but disarticulated vertebrate skeletons or isolated bones.
3. When the sea flooding a peneplain a rather uniform facies can be expected to form that is only accentuated by a depositional relief that formed in response to hydraulic processes such as waves and currents. However, in the Early Jurassic strata of the study area exhibited small-scale facies and thickness variations. Consequently additional factors have to be considered to modulate these patterns.

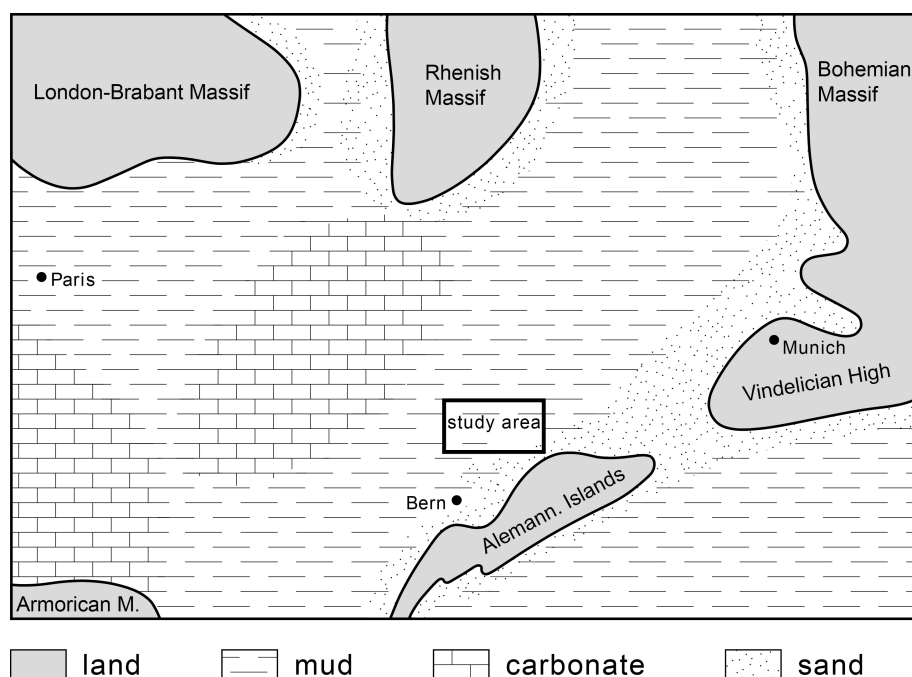


Fig. 1: Palaeogeographic map for the Early Jurassic in NW Switzerland and adjacent parts of France and Germany (modified after Ziegler 1990; Wetzel & Reisdorf 2007).

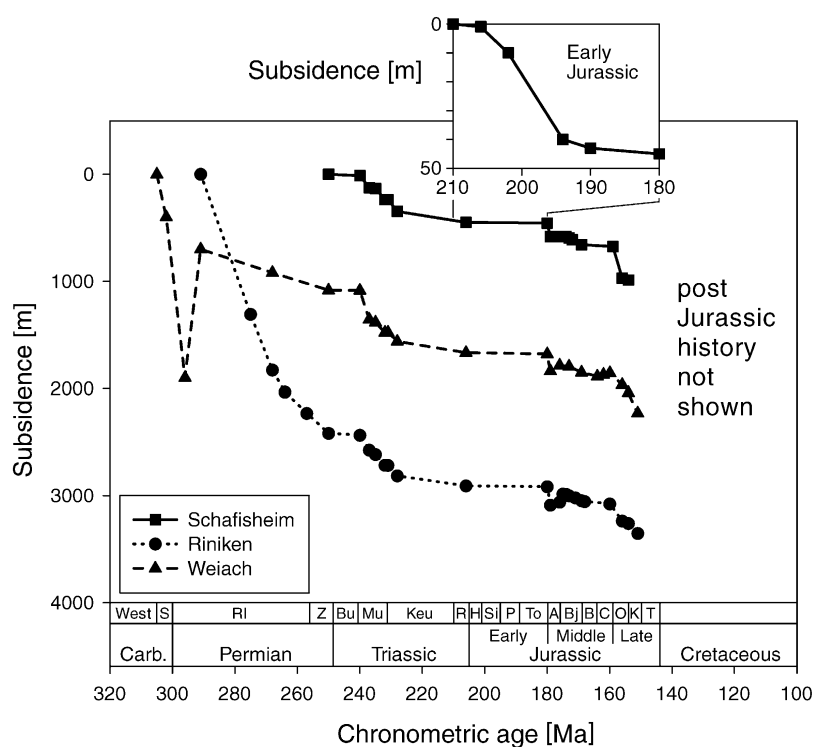


Fig. 2: Decompacted sediment thickness versus time for the standard sections drilled at Weiach, Riniken, and Schafisheim (NW Switzerland; for location, see Chapter I of this thesis, from Wetzel et al. 2003).

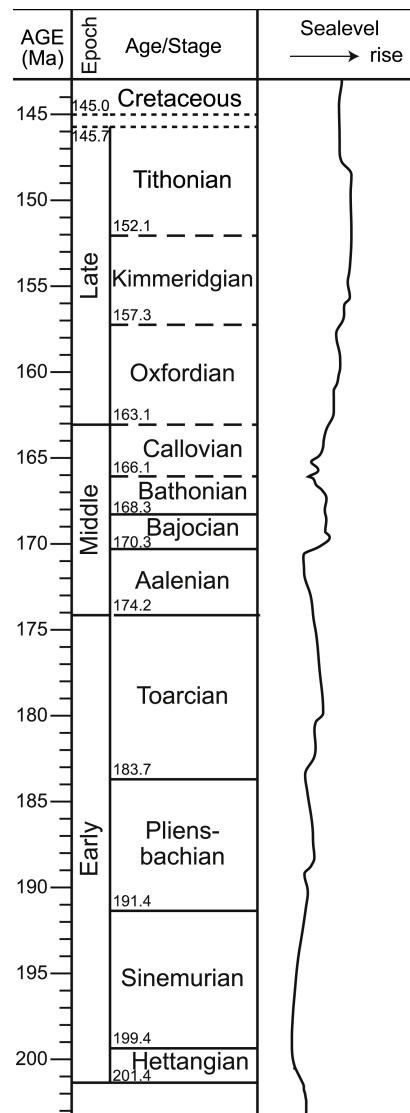


Fig. 3: Schematic sea-level curve for the Jurassic time interval (modified after Ogg et al. 2016).

These main objectives are addressed in the three main chapters of this thesis:

Chapter 1: The Staffelegg Formation: A New Stratigraphic Scheme for the Early Jurassic of Northern Switzerland

Chapter 2: Float, Explode or Sink: The Postmortem Fate of Lung-Breathing Marine Vertebrates

Chapter 3: Evidence for syndepositional differential tectonic movements in a low subsidence setting: Early Jurassic in northwestern Switzerland.

In detail, **chapter 1** describes and classifies the full-marine Early Jurassic sediments of NW Switzerland, which as a whole are usually 25 to 50 m in thickness, and which were deposited in the transitional area between the southwestern part of the Swabian Basin and the Paris Basin. These sediments are dominated by terrigenous fine-grained deposits, but calcarenitic and phosphorite-rich strata are intercalated. Unlike in the neighbouring regions of SW Germany and E France, they have a very complex stratigraphic architecture characterised by narrow abrupt facies changes, inconsistent erosive truncations and layer gaps. Despite many common features, these characteristics deviate so much from occurrences of a similar age in SW Germany and E France that it justifies the definition of discrete lithostratigraphic units that are merged in the “Staffelegg Formation”. This aspects were published by Reisdorf, A.G.; Wetzel, A.; Schlatter, R. & Jordan, P. (2011): The Staffelegg Formation: a new stratigraphic scheme for the Early Jurassic of northern Switzerland. – *Swiss Journal of Geosciences*, 104(1): 97-146.

Chapter 2 deals with the taphonomy of lung-breathing vertebrates, particularly ichthyosaurs, which were fully adapted to marine existence and were prevalent during the Early Jurassic in the southern part of the Central European Epeiric Sea. Since the skeletal preservation of ichthyosaurs is suitable as a sea-level proxy, the postmortem fate of ichthyosaurs has essential implications for the palaeobathymetry of these epicontinental depositional areas. By means of the statistical evaluation of their taphonomically patterns, so-called “ichthyosaur corpse curves” were constructed for NW Switzerland, SW Germany and England. These correlate well with other estimates of the global sea-level during the Early Jurassic by Hallam (e.g., Hallam 2001). The methodology is outlined by Reisdorf, A.G.; Bux, R.; Wyler, D.; Benecke, M.; Klug, C.; Maisch, M.W.; Fornaro, P. & Wetzel, A. (2012): Float, explode or sink: postmortem fate of lung-breathing marine vertebrates. – *Palaeobiodiversity and Palaeoenvironments*, 92(1): 67-81.

Chapter 3 represents a case study demonstrating synsedimentary tectonics in slow subsiding marine depositional area within a wide epicontinental basin. The study area in NW Switzerland and adjacent SW Germany and E France formed part of the so-called Germanic Basin or Central European Epicontinental Sea. During the late Palaeozoic the basement was structured by deep-reaching faults when a mega-shear zone developed between the Urals and the Appalachians at the end of the Variscan orogeny within the study area (Arthaud & Matte 1977). Within the study area the Rhenish Lineament, the Wehra–Zeininger Fault Zone and the North Swiss Permocarboniferous Trough system are important structural elements (Fig. 4). As the isopach and facies patterns of the Early Jurassic Staffelegg Formation above the Rhenish Lineament and the North Swiss Permocarboniferous Trough system clearly demonstrate, these late Palaeozoic fault systems became –at least temporarily– reactivated during this period of time. In addition, enhanced hydrothermal activity is documented by the chronometric age of veins and mineral alterations within both, crystalline basement and sediment cover. These data imply extensional tectonic movements that, however, are only expressed by subtle changes on the Early Jurassic

seafloor while Triassic evaporates attenuated the movements, which were generally small. These aspects are dealt with by Reisdorf, A.G. & Wetzel, A. (2018): Evidence for synsedimentary differential tectonic movements in a low-subsidence setting: Early Jurassic in northwestern Switzerland. – Swiss Journal of Geosciences, 111 (3): 417-444.

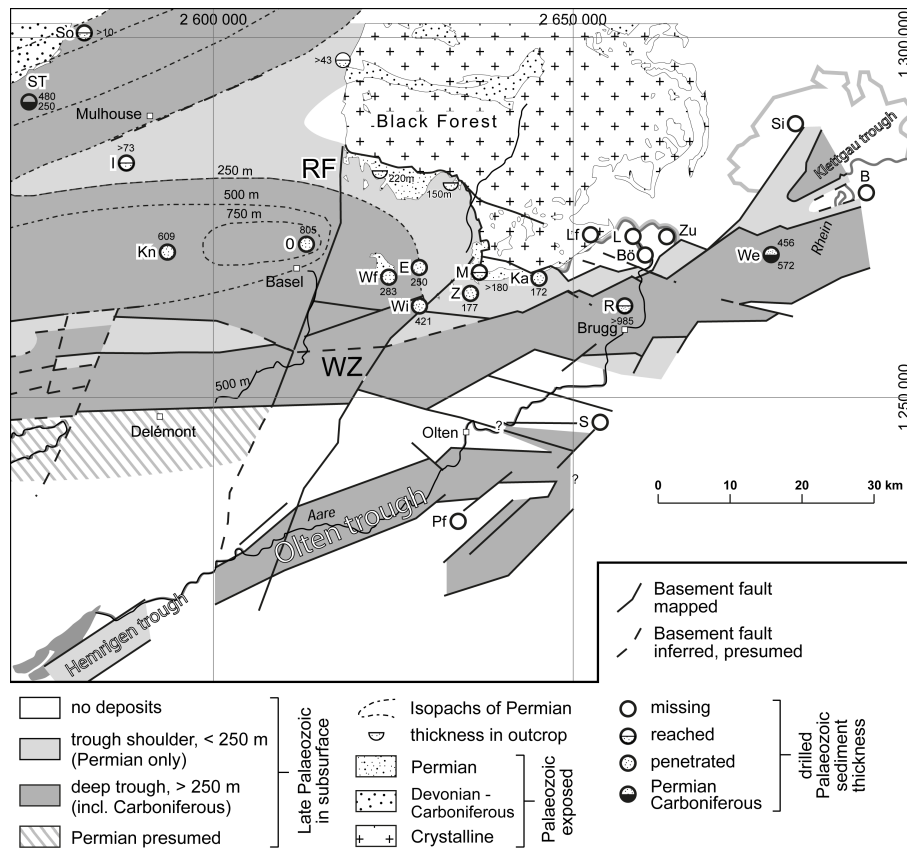


Fig. 4: Known Permian and Carboniferous troughs and faults in NW Switzerland and adjacent parts of France and Germany; modified after Wetzel (2008). RF: Rhenish Lineament; WZ: Wehra-Zeiningen Fault Zone.

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Chapter I

Lithostratigraphy: Staffelegg Formation

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The Staffelegg Formation: a new stratigraphic scheme for the Early Jurassic of northern Switzerland

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Abstract The deposits of the Early Jurassic in northern Switzerland accumulated in the relatively slowly subsiding transition zone between the southwestern part of the Swabian basin and the eastern part of the Paris basin under fully marine conditions. Terrigenous fine-grained deposits dominate, but calcarenitic and phosphorit-rich strata are intercalated. The total thickness varies between 25 and 50 m. In the eastern and central parts of N Switzerland, sediments Sinemurian in age constitute about 90% of the total thickness. To the West, however, in the Mont Terri area, Pliensbachian and Toarcian deposits form 70% of the total thickness. Stratigraphic gaps occur on a local to regional scale throughout N Switzerland. Such hiatus comprise a subzone to a stage in time. With respect to lithology and fossil content, the Early Jurassic deposits in northern Switzerland are similar to those in SW Germany. Nonetheless, an exact stratigraphic correlation is hardly possible, particularly in the southern and southwestern Folded Jura where distinct facies changes occur over short distances. Revised existing and new litho- and biostratigraphic data form the base to refine the stratigraphic subdivision of the deposits that have been informally called “Lias”. The name Staffelegg Formation is suggested and defined as the mapping unit for the Early Jurassic. The Staffelegg Formation is introduced for Early Jurassic

sediments in northern Switzerland between the Doubs River and Mt. Weissenstein in the west and the Randen Hills located north of the city of Schaffhausen in the east. The Staffelegg Formation starts within the Planorbis zone of the Hettangian. The upper boundary to the overlying Aalenian Opalinus-Ton is diachronous. The lithostratigraphic names previously in use have been replaced by new ones, in accordance within the rules of lithostratigraphic nomenclature. The Staffelegg Formation comprises 11 members and 9 beds. Several of these beds are important correlation horizons in terms of allostratigraphy. Some of them correspond to strata or erosional unconformities encountered in the Swabian realm, some of them can be correlated with strata in the Paris basin. The facies transition to the Paris basin is expressed by introduction of a corresponding lithostratigraphic unit.

Keywords Jura Mountains · Staffelegg Formation · Rhaetian · Lias · Lithostratigraphy · Allostratigraphy · Chronostratigraphy

Zusammenfassung Die Sedimente des Früh-Juras der N-Schweiz wurden in dem insgesamt etwas langsamer subsidierenden Übergangsbereich zwischen dem südwestlichen Teil des Schwäbischen Beckens und dem Pariser Becken unter vollmarinen Bedingungen abgelagert. Terrigen-klastische Pelite herrschen vor, die von kalkarenitischen und phosphoritreichen Einschaltungen untergliedert werden. Die Mächtigkeit des Früh-Juras variiert zwischen 25 und 50 m. Sedimente des Sinemuriums machen im östlichen und zentralen Bereich der N-Schweiz bis zu 90% der Mächtigkeit aus, nach Westen hingegen, im Mont-Terri-Gebiet, repräsentieren Sedimente des Pliensbachiums und

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Toarciens 70% der Mächtigkeit. Gebietsweise sind für bestimmte Zeitabschnitte des Früh-Juras keine Sedimente überliefert. Solche Hiatus können zeitlich eine Subzone bis Stufe umfassen. Die Abfolgen in der N-Schweiz ähneln hinsichtlich Lithologie und Fossilinhalt denen SW-Deutschlands, sind aber nur bedingt mit der südwestdeutschen stratigraphischen Nomenklatur in Einklang zu bringen, vor allem im Bereich des südlichen und westlichen Faltenjuras. Hier treten engräumig abrupte Fazieswechsel auf. Basierend auf revidierten, bestehenden und neuen litho- und biostratigraphischen Daten wird für die Schichtfolge, die bisher informell als “Lias” bezeichnet wurde, der Name “Staffellegg-Formation” vorgeschlagen und für die N-Schweiz als Kartiereinheit definiert. Die Staffellegg-Formation beginnt mit der Planorbis-Zone des Hettangiums. Die Grenze zur nächst jüngeren Formation, dem Opalinus-Ton, ist heterochron. Die bisher für die frühjurassischen Schichten verwendeten Bezeichnungen wurden durch neue, den heutigen Nomenklatur-Regeln konforme Namen ersetzt. Insgesamt werden für die Staffellegg-Formation 11 Member und 9 Bänke definiert. Etliche dieser Bänke sind im Sinne der Leitflächen-Stratigraphie wichtig: Ein Teil von ihnen lässt sich mit Schichten oder Erosionshorizonten im Schwäbischen Becken korrelieren, ein anderer Teil mit Horizonten im Pariser Becken. Der Faziesübergang zum Pariser Becken führt im westlichen Untersuchungsgebiet zu einer entsprechend angepassten lithostratigraphischen Untergliederung.

Résumé Les dépôts du Jurassique inférieur du nord de la Suisse se sont accumulés dans la zone de transition, en lente subsidence, entre la partie sud-ouest du bassin de Souabe et la partie orientale du bassin de Paris, dans des conditions entièrement marines. Les dépôts terrigènes pélitiques dominent; des couches calcarénitiques et riches en phosphates y sont intercalées. L'épaisseur de ces dépôts varie entre 25 et 50 mètres. Dans les parties orientale et centrale du nord de la Suisse, les sédiments d'âge Sinémurien constituent 90% de cette épaisseur, alors qu'à l'ouest, dans la région du Mont Terri, ceux du Pliensbachien et du Toarcien en constituent 70%. Des lacunes stratigraphiques apparaissent à l'échelle locale et régionale dans tout le nord de la Suisse. Ces hiatus vont de la sous-zone à la étage. Les sédiments du Jurassique inférieur du nord de la Suisse sont similaires à ceux du sud-ouest de l'Allemagne du point de vue lithologique et de leurs fossiles. Une corrélation stratigraphique exacte est cependant difficilement possible, en particulier dans les parties sud et sud-ouest du Jura plissé où de nets changements de faciès apparaissent sur de courtes distances. Sur la base de

données litho- et biostratigraphiques existantes et révisées ou nouvelles, nous proposons, pour désigner ces séries appelées jusqu'à présent de manière informelle “Lias”, le nom de “Formation de la Staffellegg”, qui servira dorénavant d'unité cartographique. Cette formation commence dans la Zone à Planorbis de l'Hettangien. La limite avec les Argiles à Opalinus aaléniennes sus-jacentes est hétérochrone. Les appellations utilisées jusqu'à présent pour ces séries du Jurassique inférieur ont été remplacées par de nouveaux noms en conformité avec les règles de nomenclature qui prévalent de nos jours. Au total, 11 membres et 9 bancs ont été définis pour la Formation de la Staffellegg. Plusieurs de ces bancs représentent d'importants horizons de corrélation en terme de stratigraphie séquentielle: certains correspondent à des couches ou surfaces d'érosion qui se retrouvent dans le bassin de Souabe, d'autres avec des horizons du bassin de Paris. La transition de faciès en direction du bassin de Paris requiert une subdivision lithostratigraphique adaptée en conséquence.

Institutional abbreviations

CTB	Collection of Thomas Bolinger (Olsberg/AG)
FPJ	(collection of the) Fondation Paléontologique Jurassienne, Glovelier/JU
IGUB	(collection of the) Institut für Geologie der Universität Bern
NMB	(collection of the) Naturhistorisches Museum Basel
NMO	(collection of the) Naturmuseum Olten

1 Introduction

1.1 History of Jurassic stratigraphy of northern Switzerland

The term Jurassic is directly linked to the Swiss Jura Mountains (Fig. 1). Alexander von Humboldt recognised the mainly limestone-dominated mountain range of the Swiss Jura Mountains as a separate formation that was not, at the time, included in the established stratigraphic system defined by Abraham Gottlob Werner and named it “Jura-kalk” in 1795 (Hölder 1950, 1964). The separation of the term Jurassic into three sections goes back to von Buch (1839). Keferstein (1825), Thurmann (1832), Roemer (1836), and von Buch (1839) were the first who assigned the term “Lias”, previously used in England, to the lowest part of the three Jurassic sections (for more details of the term Lias see Arkell 1956; Donovan and Hemingway 1963; Hains and Horton 1969).

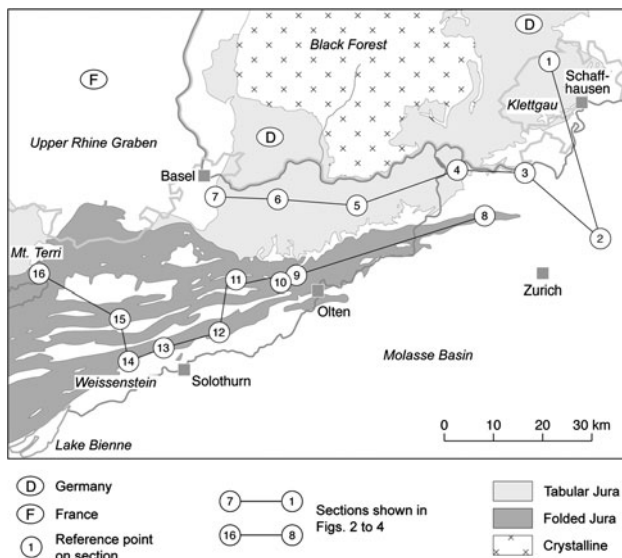


Fig. 1 Geological overview of the study area, situated in northern Switzerland, and legend of symbols used in Figs. 2, 3, 4

The Jurassic stratigraphy of northern Switzerland is closely linked to that of central and western Europe. Although related to the stratigraphic studies in central and western Europe, the Jurassic stratigraphy of northern Switzerland developed differently in many aspects. This is not only due to the more or less pronounced lithologic variations, compared to Mid- and Western Europe, but also to the fact that Switzerland is a multilingual country (Rominger 1846; Studer 1853, 1872; Moesch 1857; Disler 1941; Schweizerische Geologische Kommission, Arbeitsgruppe für Stratigraphische Terminologie 1973). The following institutions have had a considerable influence on Swiss stratigraphic nomenclature:

- Büro der Schweizerischen Geologischen Kommission (later Geologische Landesaufnahme): Einheitslegende für den Geologischen Atlas der Schweiz 1:25,000 (cf. Lang 1892; Aeppli 1915; Buxtorf and Schwarz 1960),
- Schweizerische Geologische Kommission, Arbeitsgruppe für Stratigraphische Terminologie (1973) and
- Schweizerisches Komitee für Stratigraphie (SKS; Remane et al. 2005).

Since Hedberg (1976), the International Commission on Stratigraphy has decided on an internationally valid standard for the stratigraphic classification of rocks that is based on a clear lithostratigraphic concept. The Swiss Committee of Stratigraphy (SKS) has a mandate to enforce this concept in Switzerland (Remane et al. 2005). The Swiss Committee of Stratigraphy receives support in this from the Swiss Geological Survey, which, in turn, is

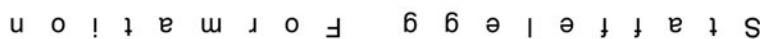
responsible for the publishing of geological maps. Both institutions have a shared responsibility for establishing a database (under development) that is linked to the internet, which names from the Swiss stratigraphy and their validity can be queried (www.stratigraphie.ch).

Unlike in Germany and France, the Early Jurassic stratigraphy in northern Switzerland is mainly based on geological mapping and less on palaeontological studies and, therefore, on lithostratigraphy. The first stratigraphic subdivision of the northern Swiss Mesozoic was established by Peter Merian (1821, 1831). Reflecting his education by Johann Friedrich Ludwig Hausmann at the University of Göttingen, his stratigraphic concept was strongly influenced by the stratigraphic subdivision in northern Germany (Buxtorf 1940). In contrast, Thurmman (1832, 1836) and Gressly (1841, 1853) followed the stratigraphy used in France and England.

Reflecting the pioneering litho- and biostratigraphic studies of Quenstedt (1843, 1858) and Oppel (1856–1858), stratigraphy established in southwestern Germany increasingly influenced that in northern Switzerland (e.g., Rominger 1846; Heer 1852; Marcou 1857a, b; Waagen 1864; Greppin 1870; Mathey et al. 1872). Nonetheless, some elements of the French stratigraphic subdivision were kept (e.g., Gressly 1853; Desor 1856; Rollier 1898; Tobler 1905; Leuthardt 1933). Because of the lack of a uniform nomenclature, French and German terms were mixed along the borders between western and northern Switzerland (e.g., Gressly 1853; Studer 1853, 1872; Mayer-Eymar 1864).

Another attempt to establish a uniform and generally applicable stratigraphical subdivision was the legend for the “Geologischer Atlas der Schweiz 1:25’000”, since 1930 (Buxtorf and Schwarz 1960). At this time, the deposits of the Opalinum zone were included in the Liassic (i.e. “Lias”), in accordance with the French nomenclature (e.g., Frank 1930; Bureau der Geologischen Kommission 1936). Later, the mapping unit “Lias” was extended to include the sediments of the Rhaethian as well (e.g., Buxtorf and Christ 1936; Tschopp 1960). However, this use was not made mandatory for all of Switzerland (e.g., Disler 1941; Buser 1952).

During the International Congress on the Jurassic in Luxemburg (1962, Colloque du Jurassique à Luxembourg), a standard stratigraphic subdivision of the Jurassic was recommended. Biostratigraphically, the Liassic spans the period from the Hettangian to the Toarcian (i.e. Planorbis to the Levesquei zone after Dean et al. 1961; see Hölder 1963). According to this definition, the Liassic was biostratigraphically shorter than the Early Jurassic, which also includes the Planorbis to Concavum zones (Hettangian to Aalenian; e.g., Hölder 1962, 1963). Later, in 1967 at the “Colloque du Jurassique à Luxembourg”, it was decided to establish a biostratigraphic range for the Early Jurassic



◀ **Fig. 2** Names of the Early Jurassic rocks (“Lias”) and its subunits previously in use (for legend see Fig. 3). Fe-Oolith. L. = Fe-Oolithische Lagen; FJ = Folded Jura; G. = Gächlingen Bed; G.Bd. = Gipf Bed?; Ins. Merg., Insektenm. = Insektenmergel; O. biod. L. = Obere Biodetritische Lage; O. spätig-biod. L. = Obere spätig-biodetritische Lagen; Pleyd.-B. = Pleydellien-Bank; Pleydellienb. = Pleydellienbank; Schamb. = Schambelen Member; Sch., -sch. = Schichten; TJ = Tabular Jura; U. biod. L. = Untere Biodetritische Lage; U. sp. biod. L. = Untere spätig-biodetritische Lagen; VH = Variabilis-Horizont; VS = Variabilis-Schichten; # = zones sensu Dean et al. (1961), sensu Bloos (1979) and sensu Schlegelmilch (1992); I = Psilonotenbank (e.g., LGRB 2004; Bloos et al. 2005; Eetzold et al. 2010); II = Oolithenbank (e.g., Schloz 1972; Bloos et al. 2005; Schmid et al. 2008); III = Kupferfelsbank (e.g., LGRB 2004; Schmid et al. 2008); IV = Davoei-Bank (e.g., Schlatter 1991; LGRB 2004); V = Unterer Stein (e.g., Urlichs 1977; Röhl and Schmid-Röhl 2005); * = likely

congruent to that of the Liassic (i.e. Planorbis to Levesquei zone; Hallam 1975). This stratigraphic nomenclature reached consensus in Switzerland with the foundation of the Arbeitsgruppe für Stratigraphische Terminologie in 1971 (now: Schweizerisches Komitee für Stratigraphie).

The majority of lithostratigraphic terms of the N Swiss Early Jurassic that are in use today were adapted from the stratigraphy of SW Germany (cf. Studer 1872; Buser 1952; Waibel and Burri 1961; Fischer 1969; Müller et al. 1984). Literature from the nineteenth and twentieth centuries contains a large number of names and definitions that differ more or less significantly from the French or SW German nomenclature (Fig. 2). The few of these that became widely known, or were established in the last few years, are shown in Figs. 2 and 4.

To fulfill the rules of stratigraphic nomenclature, it is suggested to introduce the Staffelegg Formation for the strata previously subsumed as “Lias” (Fig. 3). In the stratigraphic scheme suggested here, the individual lithostratigraphic units are all dated chronostratigraphically. With the exclusive use of a chronostratigraphic hierarchy for the terms of geochronology, we are following the nomenclature of the Swiss Committee of Stratigraphy (Remane et al. 2005).

1.2 Palaeogeography and Early Jurassic stratigraphy

The continuous improvement of palaeogeographic reconstructions influenced the stratigraphic classification in northern Switzerland until now. Heer (1865) undoubtedly introduced the most lasting scheme for the Early Jurassic in northern Switzerland but also for the neighbouring areas in southern Germany (e.g., Altmann 1965; Jordan 1983; Schlatter 1990).

Investigation of the Late Triassic and the boundary to the Early Jurassic in northern Switzerland also had a significant influence on the palaeogeographic concepts for the

Early Jurassic (e.g., Erni 1926; Hölder 1964; and references therein). It was discussed whether the sandy sediments of the Rhaetian in N Switzerland are Rhaetian or Early Jurassic in age (e.g., Rollier 1898, 1917; Buxtorf 1907 vs. Erni 1910, 1926). Furthermore, the absence of marine Rhaetian sediments in large areas of N Switzerland (Fig. 5) has been interpreted as a stratigraphic gap or caused by later erosion (e.g., Erni 1910 vs. Buxtorf 1907, 1910; Schalch and Peyer 1919; Eetzold and Schweizer 2005; Eetzold et al. 2010).

The stratigraphic and palaeogeographic considerations were the base to reconstruct the land-sea distribution in Germany and Switzerland in Rhaetian to Sinemurian times (Ehrat 1920; Pratje 1924; Rüger 1924). Particularly the direction of the transgression of the Early Jurassic sea was discussed for a many years (e.g., Wepfer 1925; Hölder 1964). This dispute, known in the literature as the “Stratigrapher War” (Wetzel 1932), chiefly concerned Vollrath’s (1924) hypothesis, which, based on the use of the index fossil method, posited that Early Jurassic sediments could not be subdivided into individual biostratigraphic units but could, instead, be grouped into contemporaneous faunal provinces. During and after the 2nd World War, stratigraphic studies on the Triassic-Jurassic boundary in northern Switzerland were restricted to a local geological scale (e.g., Vonderschmitt 1941; Peyer 1943a, b, 1956). The methodological argument was finally provided by Walliser (1956a, b), based on results found in SW Germany, and he proved the opponents of Vollrath’s hypothesis right.

2 Materials and methods

While revising the stratigraphy of the Early Jurassic strata in northern Switzerland, the joint subdivision of stratigraphic successions into lithofacies units and quasi time units was used (see Lutz et al. 2005). Because of the large number of coexisting homonyms (e.g., *Insektenmergel*, *Obliqua-Schichten*; see Fig. 4) and synonyms (e.g., *Davoei-Schichten*, *Numismalis-Schichten*, *Belemnitenkalke*; see Figs. 2, 3), new, unencumbered names for the individual lithostratigraphic units were introduced.

The new stratigraphic subdivision of the northern Swiss Early Jurassic strata is based on data from many different sources (see Table 1). The most significant and high quality data comes from the Klettgau area, Tabular Jura and the eastern Folded Jura. By contrast, because of the rare outcrops, there are only patchy data from the Bernese Jura and Mont Terri area. Based on new and hitherto unpublished sections, and new and revised biostratigraphic data (ammonites, ostracodes), the chrono- and lithostratigraphic

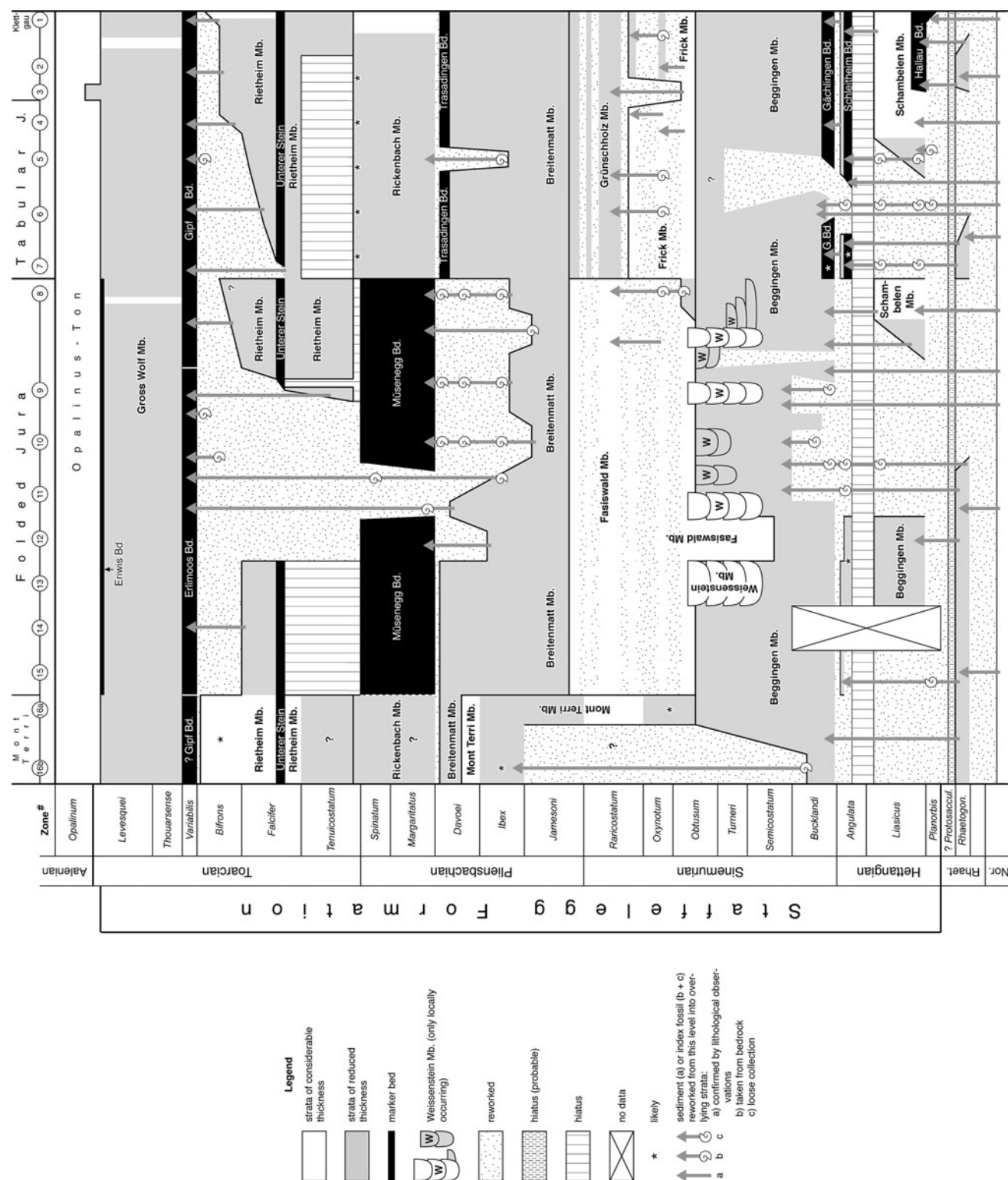


Fig. 3 Early Jurassic biostratigraphy and lithostratigraphy of northern Switzerland. Nor. = Norian; ? Protosaccul. = ? Protosacculina; Rhaet. = Rhaetian; Rhaetogon. = Rhaetogonyaulax; # = zones sensu Dean et al. (1961), sensu Bloos (1979), sensu Brenner (1986) and sensu Schlegelmilch (1992); see also Beutler et al. (2005), von Hillebrandt and Krystyn (2009), Ertzold et al. (2010). 1 Klettgau area; 2 Lindau well; 3 Weiach well; 4 eastern Tabular Jura; 5 eastern Aargau Tabular Jura

(Fig. 7); **6** western Aargau Tabular Jura (Fig. 8); **7** Basel Tabular Jura (Fig. 9); **8–9** easternmost Folded Jura (Figs. 10, 11, 12); **9** Hauenstein area (see Figs. 13, 14, 15, 16); **10** Bölchen area (see Figs. 17, 18); **11** Passwang area (see Figs. 18, 19, 20, 21); **12** eastern Weissenstein area (see Figs. 22, 23); **13** Weissenstein area (see Fig. 24); **14** Grenchenberg area; **15** Moutier area (see Fig. 25); **16** Mont Terri area (**16a** eastern area; see Fig. 26; **16b** western area; see Fig. 27)

Fe-Oolith. Lagen =
Fe-Oolithische Lagen;
Insektenm. = Insektenmergel;
Nor. = Norian;
O. biod. L. = Obere
Biodetritische Lage;
O. sp.-biodetr. Lagen =
Obere spätig-biodetritische
Lagen;
Posidon./Posidoniensch.
= Posidonienschiefer;
? Protosaccul.
= ? Protosacculina;
Psilon.-/Psiloc.-Sch.
= Psilonoten-/Psiloceras-
Schichten;
Rhaet. = Rhaetian;
Rhaetogon. =
Rhaetogonyaulax;
= zones sensu Dean et al.
(1961), sensu Bloos (1979),
sensu Brenner (1986) and sensu
Schlegelmilch (1992)

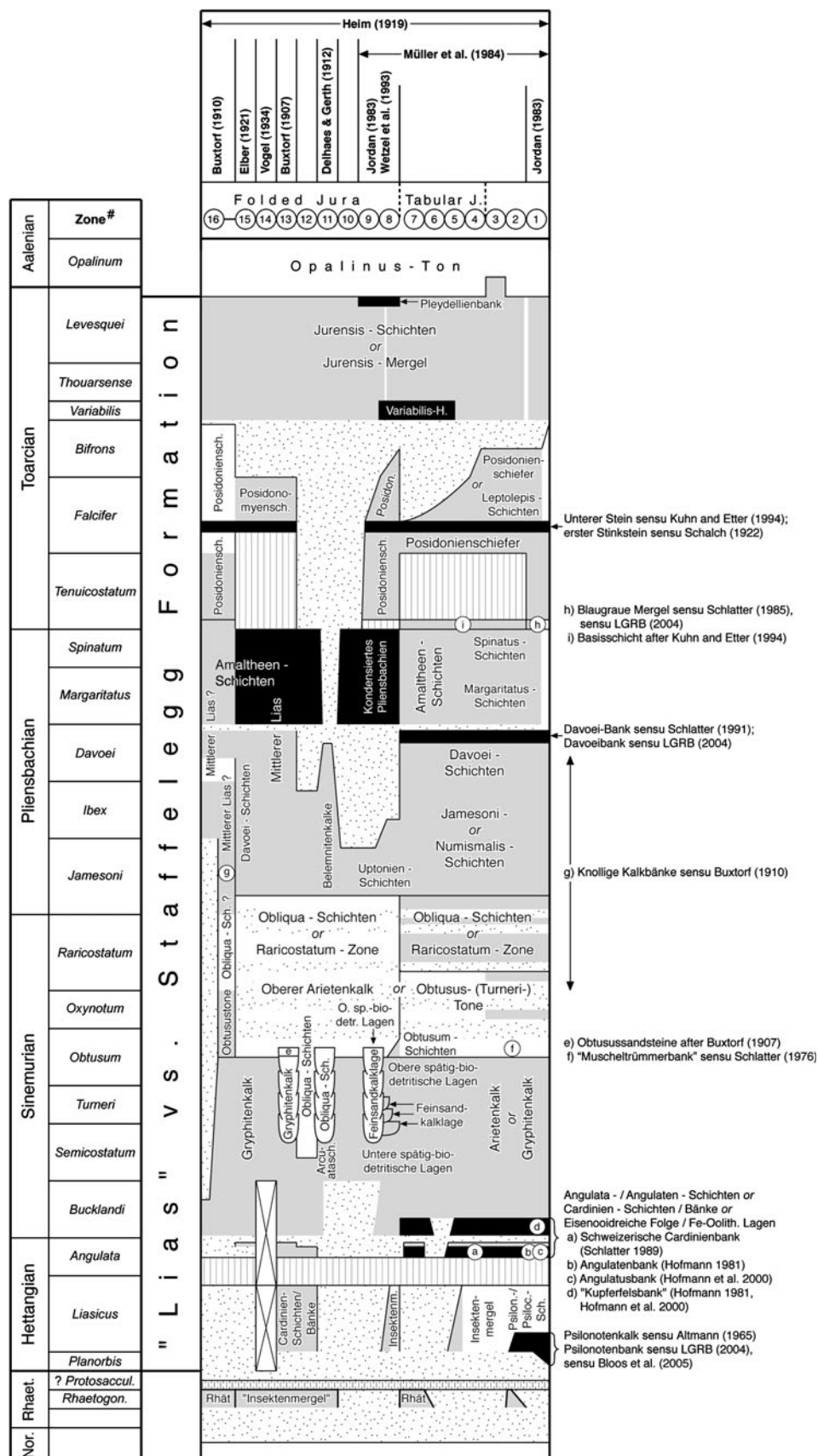
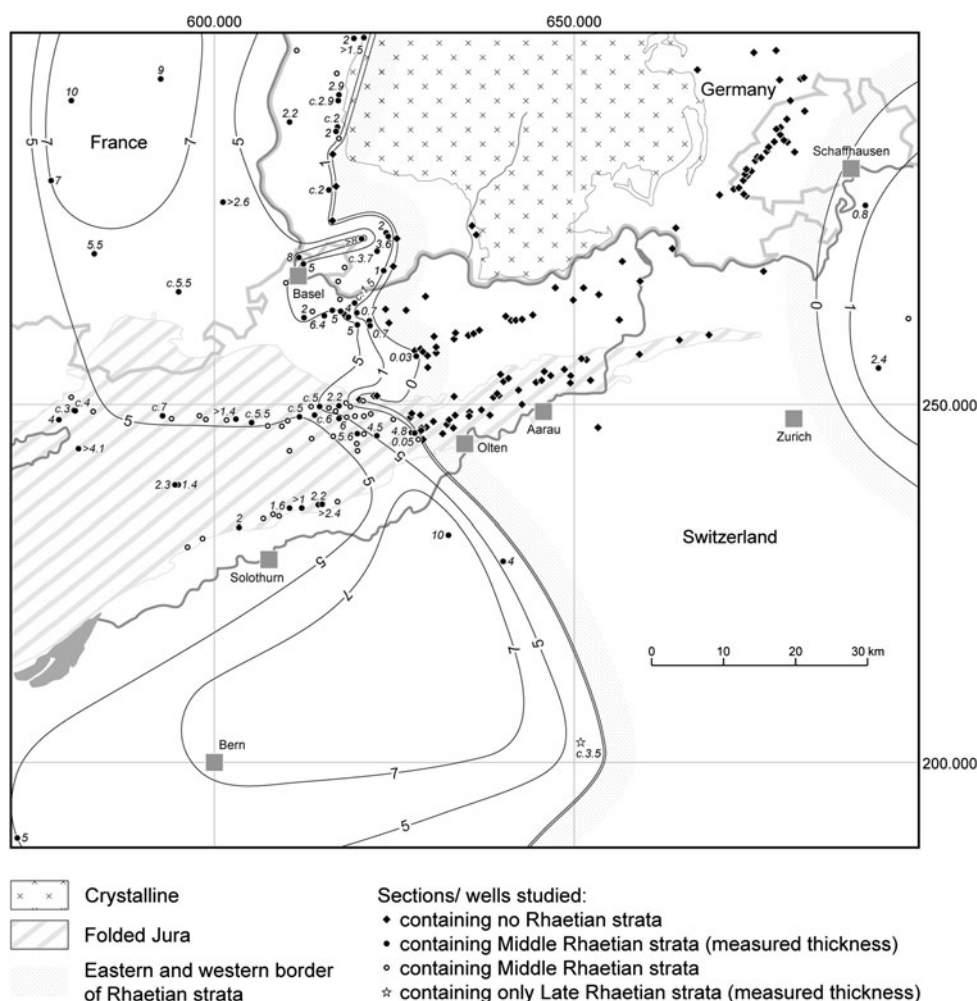


Fig. 5 Isopach map for the Rhaetian rocks in N Switzerland, SE France and SW Germany (data sources as given in Table 1)



classification of the stratigraphic inventory of the whole study area was specified more precisely.

In the past 60 years, knowledge about the facies and thickness of the northern Swiss Early Jurassic has been expanded by exploration wells drilled by the oil- and salt industry, geothermal projects, deep boreholes drilled by Nagra, ground water wells, large construction projects and also by outcrops that were made while economically exploiting Early and Middle Jurassic mudstones (e.g., Büchi et al. 1965; Hauber 1971; 2000; Meyer and Furrer 1995; Mumenthaler et al. 1997; Reisdorf 2001; Nagra 2001; Wetzel and Allia 2003; Häring et al. 2008). In addition, cores, cuttings and unpublished well data were used (see Table 1).

For biostratigraphic purposes, fossils stored in various collections were examined. Fossil finds related to the present stratigraphic scheme are mentioned in text and figures, respectively. In addition, several unpublished diploma and master theses from the Universities of Basel, Bern, Neuchâtel and Zürich, from 1957 to 2008, have been

considered; most of them are listed in the publications by Andrey (1974), Jordan (1983), Kuhn and Etter (1994) and Meyer and Furrer (1995).

3 Staffelegg Formation

Names previously in use are given in Fig. 2.

Type locality Buessge (S Thalheim/canton Aargau; coord.: 646.925/253.050 and 649.750/253.000; Jordan 1983; Fig. 10; = section Kaltenbrunnen of Erni 1910: 43).

Underlying strata Knollenmergel/Obere Bunte Mergel or “Rhät” (Middle or Late Keuper).

Overlying strata Opalinus-Ton (Early to Middle Jurassic, Late Toarcian to Early Aalenian, Levesquei to Opalinum zone).

Subdivision in the Klettgau area and Tabular Jura (from base to top) Schambelen Member, Beggingen Member,

Frick Member, Grünschholz Member, Breitenmatt Member, Rickenbach Member, Rietheim Member, Gross Wolf Member.

Subdivision in the eastern Folded Jura (from base to top) Schambelen Member, Beggingen Member, Frick Member, Fasiswald Member, Weissenstein Member, Breitenmatt Member, Rietheim Member, Gross Wolf Member.

Subdivision in the western Folded Jura (Mont Terri area; from base to top) Beggingen Member, Mont Terri Member, Breitenmatt Member, ?Rickenbach Member, Rietheim Member, Gross Wolf Member.

Occurrence Northern Switzerland.

Thickness Usually 25–50 m (Fig. 6).

Chronostratigraphic age Early to Middle Jurassic (Planorbis to Opalinum zone; Schlatter 1983a; Nagra 1989, 1990).

Description The Staffelegg Formation is a siltstone-marl-dominated heterogeneous, sedimentary succession. Additionally, limestones and subordinately also sandstones may

occur especially in the Sinemurian part. In the Folded Jura, these sediments may make up the major portion of the Staffelegg Formation. Facies changes may occur within short distances in the Folded Jura. The Staffelegg Formation displays a small thickness compared to the occurrences of the Early Jurassic of southeastern France and southwestern Germany. A gradual decrease in thickness can be detected which continues from southwestern Germany into northern Switzerland (Fig. 6; Büchi et al. 1965; Müller et al. 1984).

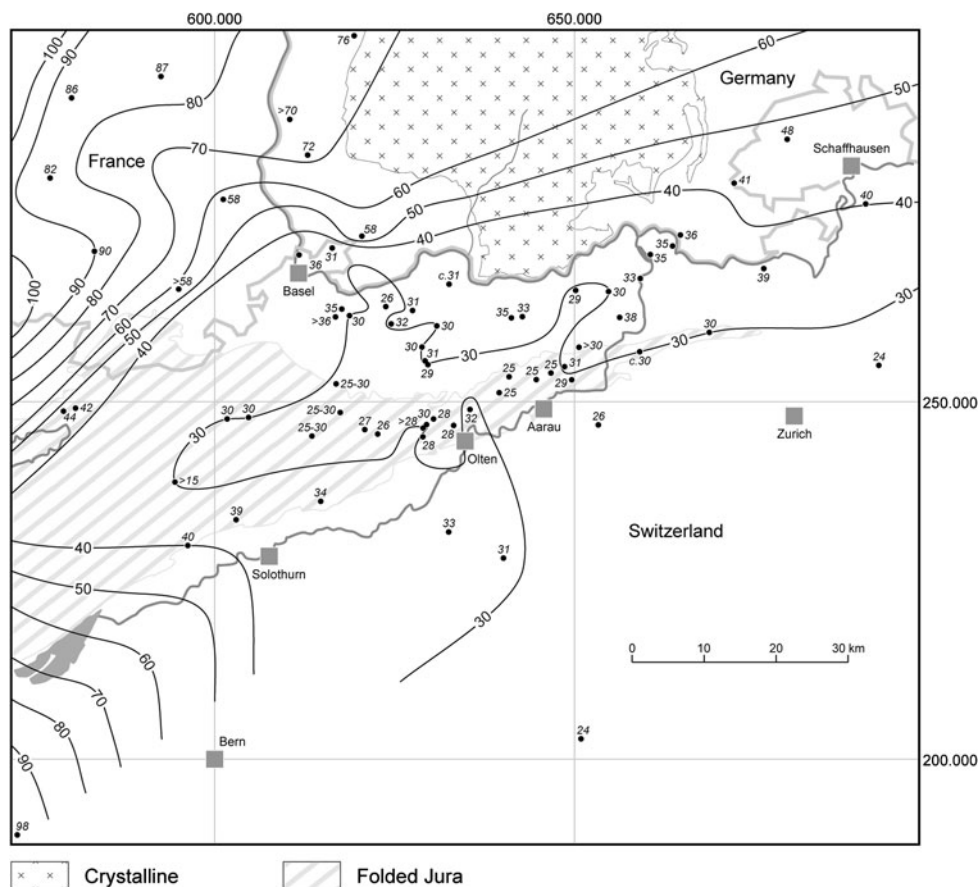
4 Lithostratigraphic subunits of the Staffelegg Formation

4.1 Schambelen Member










































Names previously in use are given in Figs. 2 and 4.

Type locality Schambelen (SW Brugg/canton Aargau; coord.: 659.310/257.000; e.g., Heer 1852; Jordan 1983; temporary exposure; excavation campaign at Schambelen

Fig. 6 Isopach map for the Early Jurassic rocks in N Switzerland, SE France and SW Germany (data sources as given in Table 1). Note that especially large uncertainties are attached to the thickness information from wells in the Molasse Basin and the Upper Rhinegraben (in particular for the determination of the Early to Middle Jurassic boundary, but also for the determination of the Early to Late Toarcian boundary; e.g., Pratje 1924; Théobald 1967; Lutz and Cleintuar 1999)



Key to sections

	sandstone		stromatolites/ sponges		gryphaeid oysters
	sandy limestone		bed rich in ammonites		brachiopods
	limestone		bed rich in belemnites		gastropods
	marly limestone		bed rich in gryphaeid oysters		sponge spicules
	silty marlstone		bed rich in <i>Cardinia</i> and/or <i>Plagiostoma</i>		stromatolites/ sponges
	marlstone		encrinite		crustaceans
	bituminous marly clay		FeOO iron ooids		insect remains
	chert		ammonites		vertebrate remains
	phosphorite		indeterminable ammonites		<i>Acrodon nobilis</i> AGASSIZ 1838 (see Kindlimann 1990)
	* glauconite		nautilids		fish remains
	+ pyrite		belemnites		plant remains
	chert nodules		☆ crinoids		bioclasts
	laminated limestone		☆ brittle star		ammonite (in place)
	phosphoritic nodules		pelecypods		ammonite (approximate stratigraphic position known)
	bioturbated nodule/surface				

1 = sensu Dean et al. (1961), sensu Bloos (1979) and sensu Schlatter (1991)
 2 = sensu Dean et al. (1961) and sensu Schlatter (1976)
 3 = sensu Dean et al. (1961)
 4 = sensu Dean et al. (1961) and sensu Bloos (1979)
 5 = sensu Dean et al. (1961) and sensu Schlatter (1991)
 6 = after Beher (2004) and Franz et al. (2009: tab. 4)

Ammonoid zones in parentheses were not verified in the studied section

7 = sensu Ulrichs (1977)
 8 = sensu Delhaes and Gerth (1912)
 9 = after Buxtorf (1907)
 10 = member of the Staffelegg Formation (this volume)
 11 = sensu Müller et al. (1984)
 12 = sensu Jordan (1983)
 13 = sensu Erni in Mühlberg (1915)
 14 = sensu Buxtorf and Christ (1936)
 15 = sensu Elber (1921)
 16 = sensu Buxtorf (1910)
 17 = sensu Wetzel and Allia (2003)
 18 = compare Mühlberg (1905, 1910)

A. = Aalenian
 Ang. = Angulata
 B. = Bucklandi
 Bifr. = Bifrons
 D. = Dogger
 Dav. = Davoei
 F. = Falcifer
 G. W. Mb. = Gross Wolf Member

H = Hettangian
 J. = Jamesoni
 J.M. = Jurensis-Mergel
 Kond. Pliens. = Kondensiertes Pliensbachien
 L. = Levesquei
 M. = Margaritatus
 Numism. Sch. = Numismalis-Schichten
 O. = Opalinum
 Ob. = Obtusum
 O. Ob.-Sch. = Obere Obliqua-Schichten
 O.S. = Opalinus-Schichten
 O. spätig-biodetr. L. = Obere spätig-biodetritische Lagen
 O.T. = Opalinus-Ton
 P.B. = Pleydellienbank
 Pliensb. = Pliensbachian
 P.S. = Posidonienschiefer
 Raricost. = Raricostatum
 R.Mb. = Rietheim Member
 S. = Spinatum
 Semicost. = Semicostatum
 T. = Thouarsense
 Ten. = Tenuicostatum
 Toarc. = Toarcian
 Tur. = Turneri
 U. sp. b. L. (Fasiswald) = Untere spätig-biodetritische Lagen
 Upton.-Sch. = Uptonienschichten
 V. = Variabilis
 V.H. = Variabilis-Horizont
 Z.P., M., D. = Zone der Posidonienschiefer, des Amm. margaritatus und Amm. Davoei
 # = *Cotteswoldia aalensis* (ZIET.) after Schulbert (2001)

by the Natural History Museum Basel and the Geologisch-Paläontologischer Arbeitskreis Frick in 2004).

Underlying strata Knollenmergel (Zanclodonmergel)/ Obere Bunte Mergel or “Rhät” (Middle and Late Keuper,

respectively; e.g., Frey 1969; Jordan 1983; Achilles and Schlatter 1986).

Overlying strata Beggingen Member or Weissenstein Member.

Subdivision Hallau Bed (only in the Klettgau area and in the Zürcher Weinland area at the base of the Schambelen Member).

Occurrence Klettgau area, Zürcher Weinland, Tabular Jura, eastern Folded Jura.

Thickness 0 to ca. 9 m (see Jordan 1983; Bitterli-Brunner and Fischer 1988; Nagra 1990, 1992).

Chronostratigraphic age Early to Late Hettangian (Planorbis to Liasicus zone; Fig. 10; Trümpy 1959; Schlatter 1983a, 1990; Achilles and Schlatter 1986; Maisch et al. 2008).

Description The Schambelen Member is mainly composed of marly terrigenous mudstone. Subordinate amounts of thin, sometimes bituminous, limestone and silt- and sandstone occur (Figs. 7, 10; see Schalch and Peyer 1919; Bader 1925; Jordan 1983; Nagra 2001). The boundary to the underlying strata is marked by an erosional unconformity (see Schalch and Peyer 1919; Altmann 1965; Achilles and Schlatter 1986). With exception of the Basel Tabular Jura, the basal portion of the Schambelen Member is bituminous, thin-bedded and has a carbonate content of 5–8% (see Tanner 1978; Jordan 1983; Schlatter 1983a). In the Klettgau area, this dark grey to black terrigenous mudstone is restricted to the Hallau Bed (= *schwarze, geradschiefrige, posidonienschieferähnliche Mergelschiefer* of Schalch and Peyer 1919; see Achilles and Schlatter 1986). Mudstone with these characteristics belongs to the Liasicus zone in the whole distribution area of the Schambelen Member, and, according to fossils found in Frick and the northern Klettgau area, possibly also to the Planorbis zone (= *Untere, bituminöse Insektenmergel* of Jordan 1983; Figs. 7, 10; Schlatter 1983a; Maisch et al. 2008). This mudstone becomes continuously greenish grey and slightly sandy upwards. The distinctive fine bedding and the bituminous content are then lost (= *Obere, schwaichelähnliche Insektenmergel* of Jordan 1983; Fig. 10). In the Klettgau area, a change to dark, greenish to brownish grey, silty to fine sandy mudstone without distinct fine bedding occurs above the Hallau Bed (= *Schwaichel*; Schalch and Peyer 1919). These sediments belong entirely to the Liasicus zone (Schlatter 1983a). To the Southwest, the Schambelen Member wedges out completely but is also present in the Basel Tabular Jura, although with a different facies (see Tanner 1978; Jordan 1983; Wetzel et al. 1993). There, this sediment is developed as dark grey to blackish, occasionally, fine sandy terrigenous mudstone containing pyrite; its biostratigraphic age was not yet determined unequivocally. Strübin (1901) listed a poorly preserved fragment of a questionable *Psiloceras* sp. from these unbedded sediments from the section Niederschönthal (= Schöntal, coord.: 621.650/261.700).

In addition, the lithostratigraphic affiliation of the limestone from the Gelterkinden—Sissach area, that contains ammonites of the Early Hettangian, is uncertain (*Psiloceras plicatulum* (QU.), det. F. Wiedenmayer 1980 [NMB J 29354]; *Psiloceras* cf. *distinctum* (POMPECKI), det. R. Zingg 1965 [NMB J 9787]; *Psiloceras* (*Caloceras*) ex gr. *johnstoni hercynum* W. LANGE, det. R. Schlatter 2006 [NMB J 33220; NMB J 33221; NMB J 33230; NMB J 33231]; cf. Berg 1961; Hölder 1964: 12; Bloos 1981).

4.1.1 Hallau Bed

Names previously in use are given in Fig. 4.

Type locality Hallau (Bratelen, Hallauerberg; canton Schaffhausen; coord.: 676.400/284.500; temporary exposure, see Achilles and Schlatter 1986).

Underlying strata Knollenmergel in the Klettgau area, “Rhät” in the Zürcher Weinland area (Middle and Late Keuper, respectively).

Overlying strata The Hallau Bed forms the base of the Schambelen Member.

Occurrence Klettgau area, Zürcher Weinland.

Thickness 0 to some 2 m (see Schlatter 1983a; Nagra 1993, 2001).

Chronostratigraphic age Early Hettangian (Planorbis to Liasicus zone, Planorbis to Portlocki subzone; Schlatter 1983a; Achilles and Schlatter 1986).

Description The definition of the Hallau Bed follows the southern German subdivision scheme of Altmann (1965; there called Pylonotenbank, see Bloos et al. 2005 and Etzold et al. 2010). The Hallau Bed is basically understood as a condensation and reworking horizon (Altmann 1965; Bloos et al. 2005). Sediments of the same age from SW Germany contain several levels with ammonite associations (e.g., Altmann 1965; Bloos 1999).

At the type locality Hallau, this condensation horizon begins with a 5–15 cm thick black marl which is rich in echinoderm remains (Schalch and Peyer 1919; Achilles and Schlatter 1986). Two distinct limestone layers follow, being separated by a 70 cm thick, thinly bedded dark brown to black, bituminous terrigenous mudstone (Schalch and Peyer 1919; Altmann 1965; Achilles and Schlatter 1986). The two limestone beds are 10–40 cm thick coquinas which regularly contain middle- to coarse-grained sand and glauconite. The upper limestone layer may contain iron ooids in addition (Schalch and Peyer 1919; Nagra 2001). In the Klettgau area, the limestone of the Hallau Bed can be completely replaced by easily weathering black



◀ **Fig. 7** Detailed section of the Early Jurassic strata at Frick (Gruhalde clay pit). α = position of the boundary between Late Hettangian and Early Sinemurian sensu Hoffmann (1934), Walliser (1956a,b) and Schlatter in Maisch et al. (2008); β = position of the boundary between Late Pliensbachian and Early Toarcian sensu Schlatter (1982), Rieggraf et al. (1984) and Kuhn and Etter (1994: *Basisschicht*); γ = *Promicroceras* cf. *planicosta* (Sow. 1814) at 7.63 m and 9.22 m (W. Etter, pers. comm. 2005); δ = *Promicroceras* cf. *planicosta* (Sow. 1814) at 16.98 m (W. Etter, pers. comm. 2005); ε = *Asteroceras* sp. at 15.72 m (W. Etter, pers. comm. 2005); ζ = “*Schlotheimia* cf. *extranodosa*” (see Maisch et al. 2008: fig. 3); η = revision of “*Psiloceras* (*Caloceras*) cf. *johnstoni* (Sow. 1824)” (see Maisch et al. 2008: fig. 3); π = compare Etzold et al. (1975); ψ = biostratigraphic range according to Jordan (1960) and Schlatter (1991)

clayey marl (see Altmann 1965). About 3 km SW of Hallau, the lower limestone layer of the Hallau Bed wedges out; therefore, the oldest sediments of the Early Jurassic are represented by roughly 25 cm of dark brown terrigenous mudstone (Altmann 1965). The wells Benken (coord.: 690.989/277.843) and Lindau 1 (coord.: 692.815/255.098) represent the southernmost localities where the Hallau Bed was encountered so far (see Altmann 1965; Frey 1969, 1978; Nagra 2001). The southernmost find of an ammonite from the Hallau Bed to date was reported 3 km SW of Hallau (Wilchingerberg; Altmann 1965: 63).

4.2 Beggingen Member

Names previously in use are given in Figs. 2 and 4.

Type locality Beggingen (Hölderli, canton Schaffhausen; coord.: 682.120/290.980; temporary exposure, Schlatter 1976).

Underlying strata Obere Bunte Mergel or “Rhät” or Schambelen Member.

Overlying strata Fasiswald Member or Weissenstein Member or Frick Member or Mont Terri Member.

Subdivision Schleithem Bed, Gächlingen Bed.

Occurrence Northern Switzerland.

Thickness From ?0 m in the Folded Jura (Jordan 1983: section Salhöchi, coord.: 641.100/253.650; see Gsell 1968: section Schürmatt, coord.: 640.160/253.160), some 1 m in the Tabular Jura (Buser 1952; Nagra 1984) to ca. 5 m in the Klettgau area (Schalch 1895), to 7 m in the Weissenstein area (Ledermann 1981).

Chronostratigraphic age Early Hettangian (Liasicus zone; Figs. 22, 23) to Late Sinemurian (Obtusum zone; Figs. 7, 8, 10; Schlatter 1976; Jordan 1983 vs. Fig. 12).

Description The Beggingen Member always lies on top of an erosive surface (Figs. 7, 8, 10, 12, 13, 14, 15, 16, 17, 18, 25, 27). It mainly consists of condensed arenitic limestone, that may be dolomitised in some cases (Fig. 18; Müller 1862; Delhaes and Gerth 1912; Jordan 1983). Individual limestone banks may end in a hardground (Fig. 10; see Jordan 1983; Wetzel et al. 1993). The following facies variations can appear at the base of the Beggingen Member:

- calcareous sandstones (Figs. 17, 22; Lehner 1920; Erni 1910, 1926; Buser 1952: 33p.; Büchi et al. 1965; Nagra 2001), which, in contrast to the Weissenstein Member, are characterised by their abundancy of *Cardinia* sp. or *Gryphaea arcuata* LAM. In general, the calcareous-shelled fossils in these arenites are corroded to a lesser or stronger degree because of diagenetic lime dissolution, bivalves (e.g., *Cardinia*

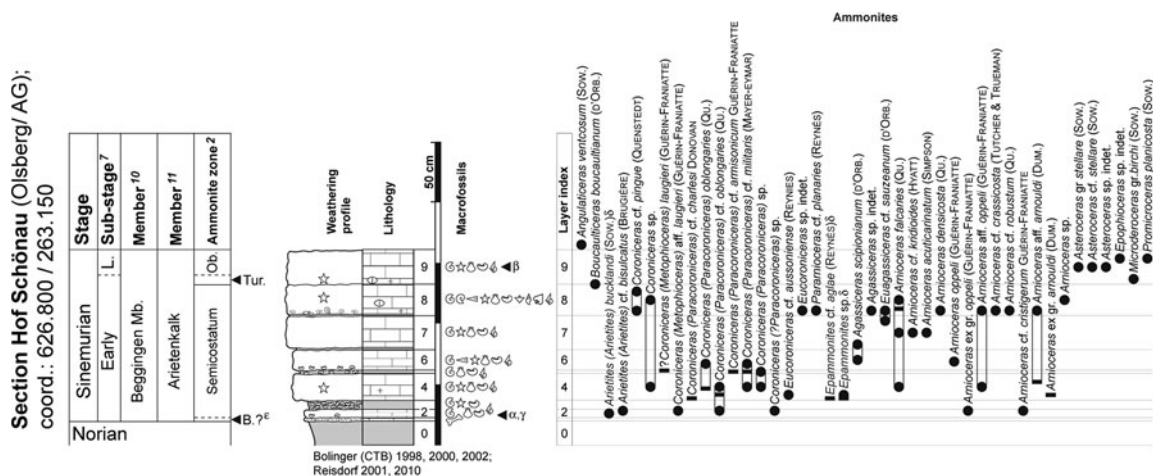
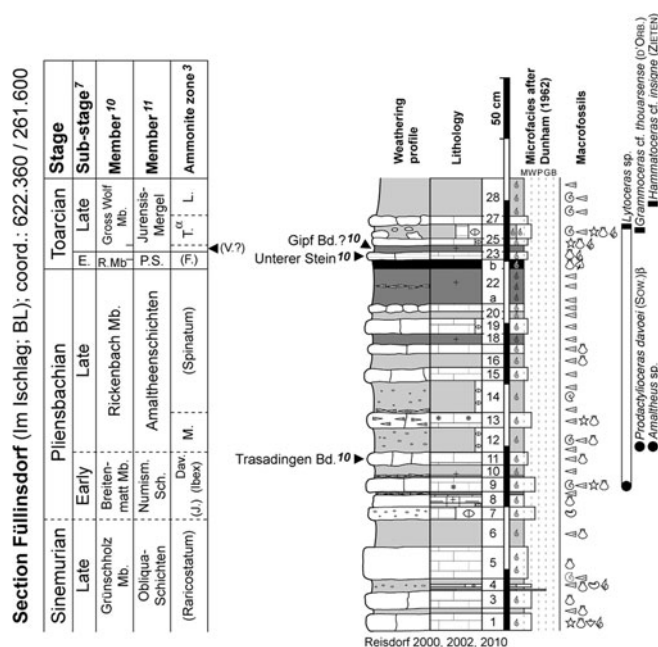


Fig. 8 Detailed section of the Early Jurassic strata at Hof Schöna (Olsberg/AG), temporary exposure. Ammonites have been collected by T. Bolinger (Olsberg/AG; CTB). α = see Pratje (1922); β = see Schlatter (1976); γ = phosphoritic, *Gryphaea*-bearing, macrofossil-

rich encrinite, highly conglomeratic in parts (packstone after Dunham 1962); δ = reworked?; ε = loosely collected *Schlotheimia* sp. (NMB J 29358; det. Wiedenmayer 1980), compare the biostratigraphic range of the genus *Schlotheimia* in Fig. 7

Fig. 9 Detailed section of the Early Jurassic strata at Füllinsdorf (Im Ischlag/BL), temporary exposure. α = loosely collected *Lytoceras* cf. *jurense* (ZIETEN); β = for the biostratigraphic range of *Productylioceras davoei* (Sow.) see Schlatter (1991)



- sp., *Gryphaea* sp.) are often only preserved as external molds (see Lehner 1920; Keller 1922; Waibel 1925).
- b) Quartz-conglomerates (Erni 1926);
 - c) dolomite-conglomerates (Lehner 1920; Erni 1926; Fig. 8);
 - d) flat pebble conglomerates (Suter 1927); more unfrequently,
 - e) limestone-breccias (Keller 1922);
 - f) bonebeds (Lehner 1920; Erni 1926; Suter 1927).

If the erosive contact of the Staffelegg Formation incises down to sediments of the Middle Keuper, then the Beggingen Member often set in with unlayered, light grey to black marls of up to 20 cm thickness (see Erni 1910; Buser 1952; Jordan 1983; Figs. 13, 14, 15, 16). In the oldest layers of the Beggingen Member (Liasicus to Bucklandi zone), bivalves commonly occur, most of which belong to the genera *Cardinia* and *Plagiostoma* (Figs. 7, 10, 24, 25, 27; see Schalch and Peyer 1919; Elber 1921; Maisch et al. 2008). These facies-dependent faunal associations were the reason to give it initially the chronostratigraphically misleading name *Cardinienschichten* (see Schleithem Bed and Gächlingen Bed). In the Klettgau area and from there in a south-western direction to the Frick area (canton Aargau), the basal layers of the Beggingen Member contain iron-ooliths (Figs. 7, 10; see Jordan 1983; Schlatter 1989). In contrast, the upper layers (Bucklandi to Obtusum zone) occur over a larger area in northern Switzerland and consist mainly of locally strongly phosphoritic arenitic limestone which are rich in fossils; the bivalve *Gryphaea arcuata* LAM. occurs in great abundance, locally rock-forming (Figs. 7, 8, 10, 12, 16, 18, 24, 25, 27; see von Buch 1839; Jordan 1983). Marl or marly terrigenous mudstone of small thicknesses is interbedded (Figs. 7, 10, see Buser 1952). In the Folded Jura, the facies of the Beggingen Member

interfingers with that of the Weissenstein Member (the Beggingen Member may in such a case even disappear completely, leaving only the Weissenstein Member; see Jordan 1983; Figs. 3, 10, 14, 15, 17, 24).

4.2.1 Schleithem Bed

Names previously in use are given in Fig. 4.

Type locality 2 km SE of Schleithem (Buckforen; canton Schaffhausen; coord.: 679.700/287.470; Schlatter 1976).

Underlying strata Obere Bunte Mergel or “Rhät” or Schambelen Member.

Overlying strata The Schleithem Bed forms the base of the Beggingen Member.

Occurrence Klettgau area, Zürcher Weinland, Tabular Jura, ?Weissenstein area (because of poor outcrop conditions, in contrast to Jordan et al. 2008, the Schleithem Bed has not been differentiated in the Weissenstein area.).

Thickness 0–65 cm (Brändlin 1911; possibly even up to 130 cm: Buxtorf 1907; Fischer and Luterbacher 1963; Fig. 24).

Chronostratigraphic age Late Hettangian (Angulata zone, Complanata subzone; Schlatter 2001).

Description At the base, the Schleithem Bed contains a large number of bivalves, especially the genera *Cardinia* and *Plagiostoma*. The Schleithem Bed always has an erosive base; in the Klettgau area and from there in southwestern direction to the Frick area, these layers are iron oololiths (Fig. 7; Schalch and Peyer 1919; Schlatter 1989; Maisch et al. 2008). In the Tabular Jura of the canton

Table 1 Compilation of data sources used for isopach maps and stratigraphic classification

Authors	Rhaetian (thickness)	Early Jurassic (thickness)	Biostratigraphic information	Lithostratigraphic information
Achilles and Schlatter (1986)	✓		✓	✓
Altmann (1965)	✓		✓	✓
Bader (1925)	✓	✓	✓	✓
Bath and Gautschi (2003)				✓
Beher (2004)			✓	
Bitterli (1960)			✓	✓
Bitterli (1992)		✓ ^a		
Bitterli and Strub (1975)			✓	✓ ^a
Bitterli-Brunner and Fischer (1988)				✓
Bitterli et al. (2000)	✓	✓		✓
Brändlin (1911)			✓	✓
Braun (1920)			✓	✓
Brenner (1986)	✓			
von Buch (1839)				✓
Büchi et al. (1965)	✓	✓	✓	✓
Bureau der Geologischen Kommission (1930)	✓	✓		✓
Buser (1952)	✓	✓	✓ ^a	✓
Buser in Gsell (1968)	✓	✓ ^a		
Buxtorf (1901)	✓		✓	✓
Buxtorf (1907)	✓	✓	✓	✓
Buxtorf (1910)	✓	✓		✓
Buxtorf and Troesch (1917)	✓	✓		✓
Buxtorf and Christ (1936)	✓	✓		✓
Debrand-Passard (1984)		✓		
Delhaes and Gerth (1912)	✓	✓	✓	✓
Einsele and Seibold (1961)	✓			
Elber (1921)	✓	✓		✓
Elber (1962)	✓			
Erb in Groschopf et al. (1977)		✓		
Erni (1910)	✓		✓	✓
Erni (1926)	✓		✓	✓
Etter (1990)			✓	✓
Etter and Kuhn (2000)				✓
Etzold and Schweizer (2005) and references therein	✓		✓	✓
Etzold et al. (2010)	✓			
Fischer and Luterbacher (1963)	✓	✓		✓
Fischer et al. (1964)	✓		✓	✓
Fischer (1964)		✓		
Frey (1969)	✓	✓		✓
Frey (1978)				✓
Genser and Sittig (1958)	✓			
Glauser (1936)	✓	✓	✓	✓
Goldschmid (1965)	✓	✓	✓	✓
Gsell (1968)	✓	✓	✓	✓
Gürler et al. (1987)		✓		
Hahn (1971)	✓	✓		✓
Häring (2002)	✓			

Table 1 continued

Authors	Rhaetian (thickness)	Early Jurassic (thickness)	Biostratigraphic information	Lithostratigraphic information
Häring et al. (2008)	✓	✓		
Hauber (1971)	✓	✓	✓	✓
Hauber (1991)	✓	✓		
Hauber (1994)		✓		
Hauber et al. (2000)	✓	✓		
Hess (1962)			✓	✓
Hofmann (1959)				✓
Hofmann (1981)	✓	✓	✓	✓
Hofmann et al. (2000)			✓	✓
Imhof in Jordan (1983)	✓	✓		
Jordan (1960)		✓		
Jordan (1983)	✓	✓	✓ ^a	✓ ^a
Kämpfe (1984)	✓ ^b	✓ ^b		
Käß (1954)		✓		
Keller (1922)				✓
Kelterborn (1944)	✓			✓
Knitter and Ohmert (1983)		✓		
Kuhn and Etter (1994)		✓	✓	✓
Ladner et al. (2008)	✓	✓		
Laubscher (1963)	✓	✓		✓
Ledermann (1981)				✓
Lehner (1920)			✓	✓
Lemcke and Wagner (1961)	✓	✓		
Lutz (1964)	✓			
Lutz and Cleintuar (1999)	✓	✓		
Lutz and Etzold (2003)	✓			
Maisch and Reisdorf 2006a, b			✓	✓
Maisch et al. (2008)	✓		✓	✓
Mandy (1907)				✓
Marie (1952)	✓	✓		
Mathey (1883)			✓	
Meyer (1916)	✓	✓		
Meyer and Furrer (1995)			✓	✓
Moesch (1874)	✓	✓		✓
Mühlberg (1905)	✓	✓		✓
Mühlberg (1908)	✓	✓	✓	✓
Mühlberg (1910)		✓		
Mühlberg (1915)	✓	✓	✓	✓
Müller (1862)				✓
Nagra (1984)	✓	✓	✓	✓
Nagra (1989)	✓	✓	✓	✓
Nagra (1990)	✓	✓	✓	✓
Nagra (1992)	✓	✓	✓	✓
Nagra (1993)	✓ ^c	✓		✓
Nagra (2001)	✓	✓	✓	✓
Ohmert in Groschopf et al. (1977)		✓		
Persoz (1982)	✓			

Table 1 continued

Authors	Rhaetian (thickness)	Early Jurassic (thickness)	Biostratigraphic information	Lithostratigraphic information
Peters (1964)				✓
Pfirter (1997)				✓
Pratje (1922)	✓	✓	✓	✓
Pratje (1924)	✓	✓		✓
Reisdorf (2001)	✓	✓	✓	✓
Reisdorf et al. (this volume)	✓	✓		
Richter (1987)			✓	✓
Rickenbach (1947)			✓	✓
Rieber (1973)			✓	✓
Riegraf (1986)			✓	
Riegraf et al. (1984)		✓		
Rollier (1910)				✓
Schaeren and Norbert (1989)	✓	✓		✓
Schalch (1880)	✓	✓	✓	✓
Schalch (1893)	✓	✓		
Schalch (1895)		✓		✓
Schalch (1900)	✓	✓		
Schalch (1916)	✓	✓	✓	✓
Schalch (1922)	✓		✓	
Schalch and Peyer (1919)	✓		✓	✓
Schegg et al. (1997)	✓	✓		
Schlatter (1976)		✓	✓	✓
Schlatter (1982)			✓	✓
Schlatter (1983a)	✓	✓		
Schlatter (1983b)			✓	✓
Schlatter (1989)			✓	✓
Schlatter (1990)			✓	
Schlatter (1991)			✓	✓
Schlatter (1999)			✓	✓
Schlatter (2000)			✓	
Schlatter (2001)			✓	
Schmidt et al. (1924)	✓	✓	✓	✓
Senftleben (1923)	✓	✓	✓	✓
Senftleben (1924)	✓	✓		✓
Söll (1965)	✓	✓		
Söll in Ernst (1989)		✓		
Sommaruga and Burkhard (1997: 46)	✓			
Stoll-Steffan (1987)	✓	✓		
Strübin (1901)			✓	✓
Suter (1915)	✓			✓
Suter (1927)	✓			✓
Tanner (1978)	✓			✓
Théobald (1961)	✓	✓		
Théobald (1967)	✓	✓		
Théobald and Maubeuge (1949)		✓		
Tröster (1987)		✓		
Trümpy (1959)			✓	

Table 1 continued

Authors	Rhaetian (thickness)	Early Jurassic (thickness)	Biostratigraphic information	Lithostratigraphic information
Trümpy (1980)		✓		
Tschopp (1960)		✓		✓
Veit and Hrubesch in Groschopf et al. (1977)	✓			
Vogel (1934)			✓	✓
Vollmayr (1971)	✓			
Vollmayr and Wendt (1987)	a	a	✓	✓
Vonderschmitt (1941)	✓		✓	✓
Vonderschmitt (1942)	✓	✓	✓	✓
Waibel (1925)	✓	✓		✓
Walliser (1956a)	✓		✓	
Walliser (1956b)	✓		✓	
van Werveke (1923)	✓	a		
Wetzel et al. (1993)	✓	✓		✓
Wetzel and Reisdorf (2007)				✓
Wirth (1968)	✓ ^b	✓ ^b		
von Wursterberger (1876)			✓	✓
Würtenberger (1867)		✓	✓	✓
Ziegler in Jordan (1983)	✓	✓		
Unpublished data				
CSD Colombi Schmutz Dorthe AG (well Wisenberg-Tunnel RB 22; SBB)	✓	✓		
CSD Colombi Schmutz Dorthe AG (well Wisenberg-Tunnel RB 23; SBB)	✓			
Geologisches Büro Dr. H. Schmassmann (well Eich, Magden)	✓	✓		
Geologisches Büro Dr. H. Schmassmann (well Grändel, Zeiningen)	✓	✓		
Geologisches Büro Dr. H. Schmassmann (well Weiere, Magden)	✓	✓		
Geologisches Büro Dr. H. Schmassmann (well Weierboden, Arisdorf)	✓	✓		
Geologisch-Paläontologisches Institut der Universität Basel (wells 34.R.1 to 34.R.4, Adlertunnel, SBB)	✓			
Geologisch-Paläontologisches Institut der Universität Basel (well 34.R.6, Adlertunnel, SBB)	✓			
Geologisch-Paläontologisches Institut der Universität Basel (well 41.R.115, Adlertunnel, SBB)	✓	✓		
Geologisch-Paläontologisches Institut der Universität Basel (wells 41.R.116 to 41.R.118, Adlertunnel, SBB)	✓			
Geologisch-Paläontologisches Institut der Universität Basel (well 41.R.120, Adlertunnel, SBB)	✓			
Geologisch-Paläontologisches Institut der Universität Basel (wells 41.R.123 to 41.R.125, Adlertunnel, SBB)	✓			
Geotechnisches Institut AG (wells 34.R.7 and 34.R.8, Adlertunnel, SBB)	✓			
Geotechnisches Institut AG (well 41.R.131, Adlertunnel, SBB)	✓			
Geotechnisches Institut AG (well 41.R.132, Adlertunnel, SBB)	✓	✓		
Geotechnisches Institut AG (well 41.R.133, Adlertunnel, SBB)	✓			
Geotechnisches Institut AG (wells 71.R.45 and 71.R.57, Umfahrung Sissach)	✓			
Geotechnisches Institut AG (well 71.R.58, Umfahrung Sissach)		✓		
Geotechnisches Institut AG (well 71.R.59, Umfahrung Sissach)	✓			
P.R.E.P.A. (Société de prospection et exploitations pétrolières en Alsace; well Blodelsheim 1)	✓	✓		
P.R.E.P.A. (Société de prospection et exploitations pétrolières en Alsace; well Knoeringue 1)	✓	✓		

Table 1 continued

Authors	Rhaetian (thickness)	Early Jurassic (thickness)	Biostratigraphic information	Lithostratigraphic information
P.R.E.P.A. (Société de prospection et exploitations pétrolières en Alsace; well BPR 5, Hartmannswiller, Soultz)	✓	✓		
P.R.E.P.A. (Société de prospection et exploitations pétrolières en Alsace; well Illfurth R1)	✓	✓		
Vereinigte Schweizerische Rheinsalinen (well S 29, Schüracher, Pratteln)	✓			
Vereinigte Schweizerische Rheinsalinen (well S 72, Eigental, Muttentz)	✓			
Vereinigte Schweizerische Rheinsalinen (well S 87, Sulz, Muttentz)	✓			
Vereinigte Schweizerische Rheinsalinen (well S 93, Gruetäcker, Muttentz)	✓			
Vereinigte Schweizerische Rheinsalinen (well S 96, Hopferen, Arisdorf)	✓	✓		
Vereinigte Schweizerische Rheinsalinen (well S 111, Eigental, Muttentz)		✓		
Vereinigte Schweizerische Rheinsalinen (wells S 116 and S 119, Auf Wartenberg, Muttentz)	✓			
Wintershall Holding AG (well Meersburg 1)	✓	✓		

^a Revised by Reisdorf et al. (this volume)

^b Revised by Stoll-Steffan (1987)

^c Revised by Etzold and Schweizer (2005: 243) and Etzold et al. (2010)

Aargau (Rietheim – Frick area), the iron oolitic facies changes into a bioclastic packstone facies (see Schalch 1980; Schalch and Peyer 1919). In the Basel Tabular Jura, the Schleithem Bed is bioclastic packstone (see Erni 1910; Tanner 1978). The ± 30 cm thick, black to yellowish marls, in which iron-containing, iron oolith to bioclastic packstone concretions are embedded are an additional facies variation (see Brändlin 1911; Buser 1952).

In the eastern Basel Tabular Jura as well as in the eastern Folded Jura, the Schleithem Bed is absent because of erosion (Figs. 14 and 17; see Buser 1952). In the Weissenstein area, similar sediments occur again, but here within the basal part of the Beggingen Member (= Schleithem Bed?; Figs. 23, 24; see Buxtorf 1907). Here, it may display an iron-oolithic facies (Fig. 22).

4.2.2 Gächlingen Bed

Names previously in use are given in Fig. 4.

Type locality 1 km WNW of Gächlingen (Lugmer, canton Schaffhausen; coord.: 678.650/284.700; temporary exposure, Schlatter 1976).

Occurrence Klettgau area, Zürcher Weinland, Tabular and Folded Jura (with an interruption possibly extending to the Weissenstein area and the Mont Terri area: In contrast to Jordan et al. 2008, because of poor outcrop conditions, the Gächlingen Bed has not been differentiated there.).

Thickness 0 to ± 50 cm (Nagra 2001; Fig. 10).

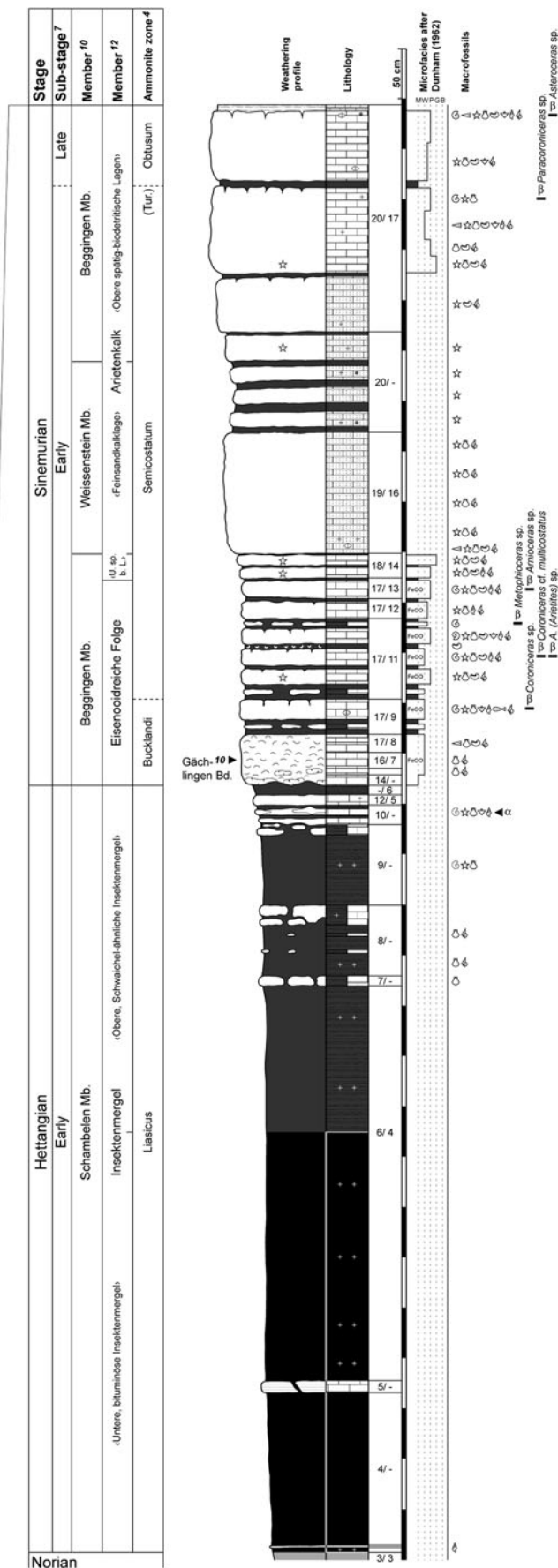
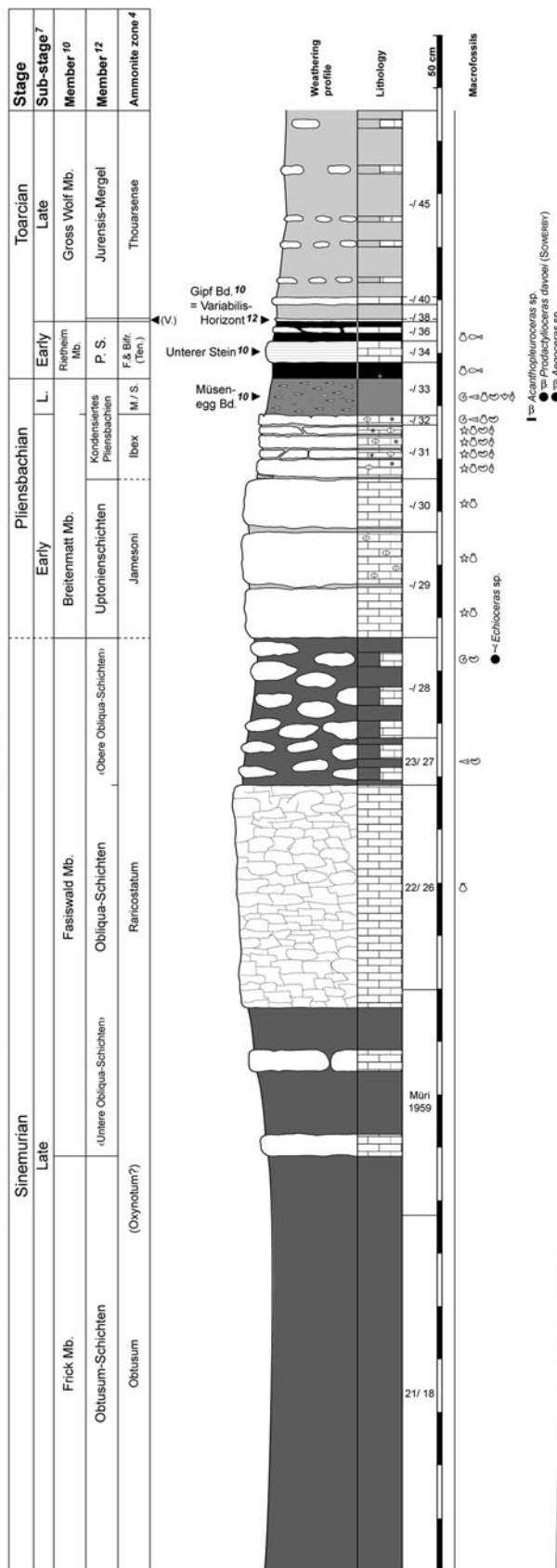
Chronostratigraphic age Early Sinemurian (Bucklandi zone, Conybeari subzone; Bloos 1976).

Description The Gächlingen Bed is included in the basal beds of the Beggingen Member (e.g., Klettgau area, Tabular Jura; Fig. 7) or at its base (e.g., Folded Jura; Fig. 10). Wacke-to packstone of small thickness, containing iron ooids (see Jordan 1983; Hofmann et al. 2000). Bivalves, especially of the genus *Cardinia*, occur occasionally in rock-forming abundance. Besides the index ammonites of the Bucklandi zone, the Gächlingen Bed can also contain ammonites of the genus *Schlotheimia* (e.g., “*Riesenangulaten*”; see Walliser 1956a; Hahn 1971; Bloos 1976; Maisch et al. 2008).

Laterally, the Gächlingen Bed may change into a duff horizon with concretionary limestone and ultimately wedges out entirely (Fig. 7; see Buser 1952; Hofmann 1981; Nagra 1989; Maisch et al. 2008).

The stratigraphic position of the coquinas (with *Cardinia* and/or *Plagiostoma*) that occur in the western part of the study area (Weissenstein area; section Hautes Roches and Mont Terri area; Buxtorf 1907 vs. Rollier 1910; Elber 1921; Erni 1926; Figs. 22, 23, 24, 25, 27) is not yet resolved beyond doubt. In these sediments, the Bucklandi zone has so far only been proven in the Mont Terri area, using a loosely collected *Angulaticeras angulatoides* (Qu.) (= section Courtemautruy, Fig. 27; note that the *Courtemautruy Bed* of Jordan et al. 2008 is no longer kept because of the lack of suitable outcrops). In addition, it should be mentioned that iron ooids have so far only been found in such limestones in the eastern Weissenstein area (Fig. 22, Erni 1910: 38 vs. Vollrath 1924: 22; Bitterli and Strub 1975; own data).

Type locality of the Staffelegg Formation: section Buessge (AG); coord.: 649.925 / 253.050 and 649.750 / 253.000



◀ **Fig. 10** Detailed section of the Early Jurassic strata at Buessge (AG), Type locality of the Staffelegg Formation. Ammonoid zones in parentheses were not verified in the Staffelegg area. α = “*Schlotheimia* sp.” (Jordan 1983) = ? *Saxoceras* sp. (see Etzold et al. 1975: 124p. and Urlichs 1977: 16p.); β = data from Jordan (1983); γ = data from Müri in Jordan (1983)

4.3 Weissenstein Member

Names previously in use are given in Figs. 2 and 4.

Type locality Käspisbergli 1 km N of Günsberg (canton Solothurn, see Rollier 1904; coord.: 610.560/235.140; Fig. 24; Buxtorf 1907).

Underlying strata Schambelen Member or Beggingen Member or Fasiswald Member.

Overlying strata Beggingen Member or Fasiswald Member.

Occurrence Eastern Folded Jura to Weissenstein area (see Pratje 1924; Bitterli and Strub 1975; Jordan 1983), well Altishofen 1 (coord.: 639.500/228.000; see Fischer and Luterbacher 1963).

Thickness Up to some 22 m (Fischer and Luterbacher 1963); facies interfingering with the Beggingen Member.

Chronostratigraphic age Early to Late Sinemurian (Semicostatum to Obtusum zone; Figs. 10, 15; Jordan 1983; loosely collected *Promicroceras* sp., E Ulmethöchi/BL, coord.: ca. 616.700/247.800 [NMB J 33219, det. R. Schlatter 2005]).

Description Beige, calcareous sandstones or sandy limestones, respectively, usually 6–22 m thick or sometimes much less (Figs. 10, 12, 13, 14, 15, 24; Delhaes and Gerth 1912; Heim 1919; Fischer and Luterbacher 1963; Wetzel et al. 1993; = *Feinsandkalklage* sensu Jordan 1983). These partially silicified and sometimes dolomitised sediments occasionally contain bluish chert concretions, but very rarely macrofossils which are of biostratigraphic use (Figs. 14, 15, 18, 23; see Delhaes and Gerth 1912; Bitterli and Strub 1975; Jordan 1983). The Weissenstein Member is characterised by spatially close facies-changes and alternations with the Beggingen Member (see Erni 1926; Buser 1952; Jordan 1983; Wetzel et al. 1993) and the Fasiswald Member, respectively (Figs. 10, 14, 15, 17, 24).

The more or less fossil-rich, sandy limestone or calcareous sandstone that are found at the base of the Staffelegg Formation in the Grindel—Erschwil area are, however, not attributed to the Weissenstein Member (see facies variations of the Beggingen Member; see Erni 1910; Lehner 1920; Keller 1922; Waibel 1925).

4.4 Frick Member

Names previously in use are given in Figs. 2 and 4.

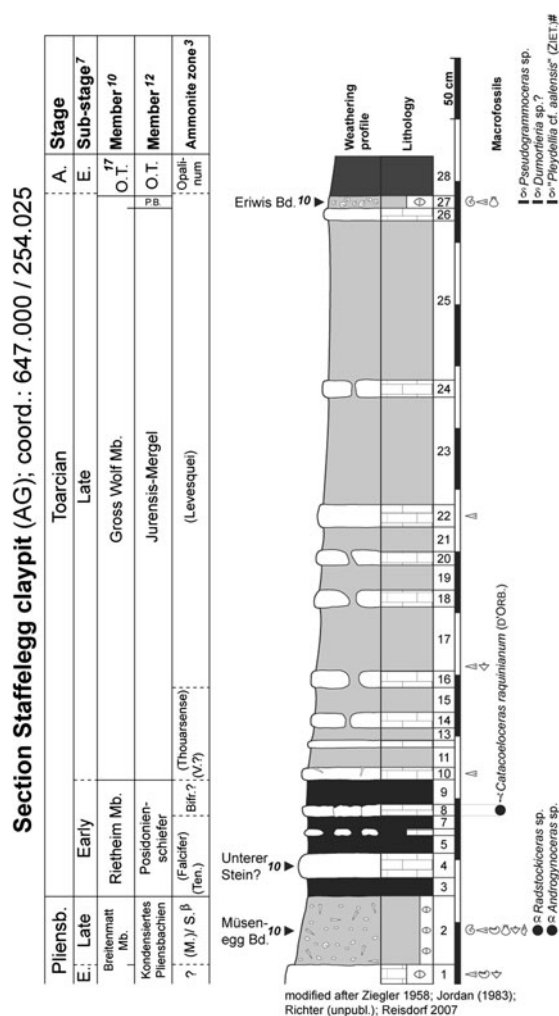


Fig. 11 Detailed section of the Early Jurassic strata at the Staffelegg clay pit (AG). α = data from Jordan (1983); β = loosely collected *Pleuroceras* sp. at the “Staffelberg” (collection of the Geologisches Institut der ETH Zürich; see Jordan 1983); γ = loosely collected (Reisdorf et al. subm.); δ = data from Ziegler in Jordan (1983)

Type locality Gruhalde clay pit in Frick (canton Aargau; coord.: 643.000/261.900; see Behr 2004).

Underlying strata Beggingen Member.

Overlying strata Grünschholz Member or Fasiswald Member.

Occurrence Klettgau area, Tabular Jura, Zürcher Weinland, eastern Folded Jura (here facies interfingering with the Fasiswald Member).

Thickness The maximum thicknesses lie around some 20 m in the Tabular Jura (Fig. 7; Gsell 1968); in the Folded Jura, however, the thicknesses are significantly below 10 m (Fig. 10; Jordan 1983).

Chronostratigraphic age Late Sinemurian (Obtusum to Raricostatum zone, Stellare subzone to

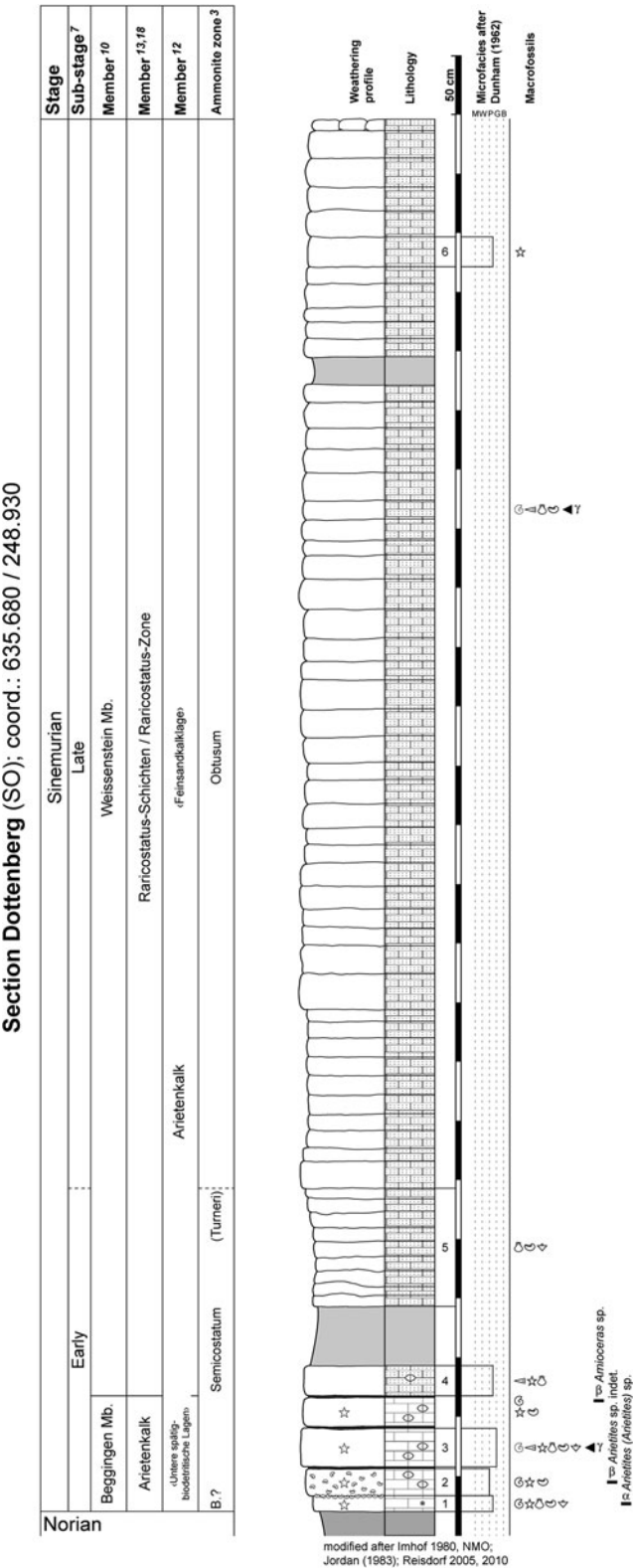


Fig. 12 continued

Hofmann 1959; Frey 1978; Schlatter 1999; Nagra 2001). Interlayering with thin, fine-grained sandstones or layers with marcasite, pyrite or clay iron-stone concretions can

occur. Lime- and/or phosphorite concretions are often seen at the top of the Frick Member (see Peters 1964; Nagra 1984, 1990; Schlatter 1991). The youngest sediments of the Frick Member can show different degrees of reworking such as flat pebble conglomerates, reworked ammonites etc. (see Schlatter 1983b, 1991; Behr 2004).

In the occurrences of the Frick Member in the eastern Folded Jura, interfingering of facies with the Fasiswald Member is observed.

Towards the southwest, the mudstone succession is significantly thinner than in the Tabular Jura and the Klettgau area, and, increasingly, limestone concretions and limestone beds are intercalated (Fig. 10; see Jordan 1983; Wetzel et al. 1993; Reisdorf 2001).

4.5 Grünschholz Member

Names previously in use are given in Figs. 2 and 4.

Type locality Grünschholz (NW Galten; canton Aargau; coord.: 651.000/265.700; see Buser 1952, outcrop no longer accessible).

Underlying strata Frick Member.

Overlying strata Breitenmatt Member.

Occurrence Klettgau area, Zürcher Weinland, Tabular Jura.

Thickness In the Klettgau area, rarely more than 1 m thick; thickness in the Tabular Jura is rarely more than 1.5 m and never above 2 m (Brändlin 1911; Schalch 1916; Gsell 1968).

Chronostratigraphic age Late Sinemurian to Early Pliensbachian (Raricostatum to Jamesoni zone, Densinodum and Raricostatum to Nodogigas and Taylori subzone; Fig. 7, Schlatter 1983b, 2000).

Description Strata consisting of calcareous marl and predominantly concretionary limestone beds containing glauconite and calcareous phosphoritic concretions (Figs. 7, 9; see Schlatter 1991, 1999). The phosphorite is mainly associated to bioturbated domains. The Grünschholz Member rest on top of an erosive surface that is more or less distinctive (Schlatter 1999; Behr 2004).

4.6 Fasiswald Member

Names previously in use are given in Figs. 2 and 4.

Type locality Fasiswald clay pit (NNW Hägendorf; canton Solothurn; coord.: 629.100/245.100; Fig. 17; cf. Erni in Mühlberg 1915).

Section Erlimoos (SO); coord.: 633.525 / 247.125

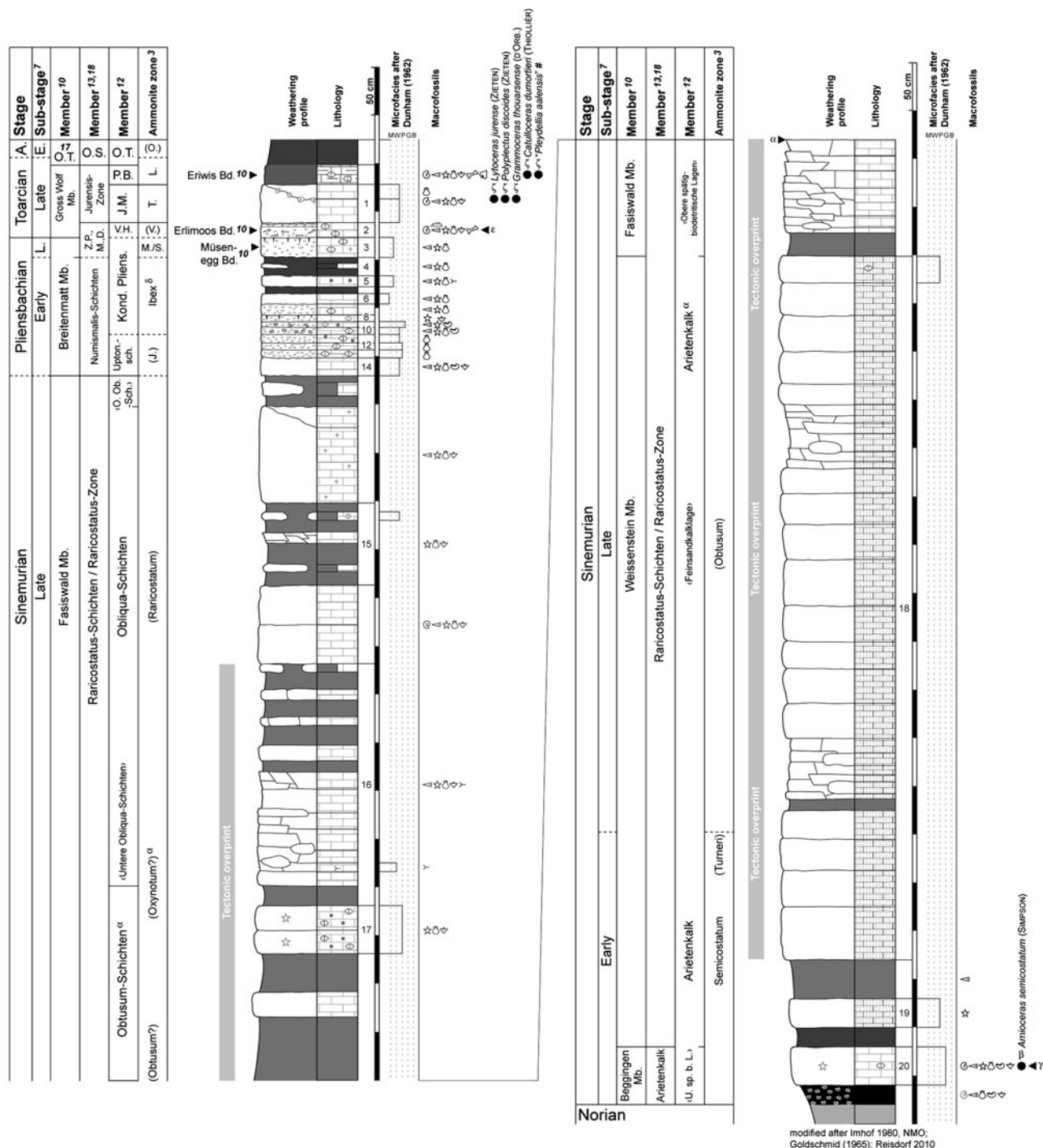


Fig. 13 Detailed section of the Early Jurassic strata at the Erlimoos clay pit (SO). α = compare Jordan (1983: section Dottenberg) and Fig. 12; β = data from Goldschmid (1965); γ = “*Coroniceras* aff. *sauzeanum* (D’ORB.)”, “*Coroniceras* aff. *bisculatum* (BRUG.)”, “*Amioceras* cf. *Bodleyi* (HYATT)”; data from Goldschmid (1965); δ = loosely collected *Acanthopleuroceras* cf. *maugenesti* (D’ORB.), *Acanthopleuroceras* sp., *Liparoceras* sp., *Beaniceras* cf. *senile* (Buckm.), *Beaniceras* sp. (own data); ϵ = *Lytoceras fimbriatum*

(Sow.), *Androgynoceras maculatum* (Y. & B.), *Androgynoceras intracarpicornus* (QU.), *Liparoceras bronni* SPATH, *Prodactylioceras davoiei* (Sow.), *Amaltheus* cf. *stokesi* (Sow.), *Pleuroceras* sp. indet., *Catacoeloceras raquinianum* (D’ORB.), *Osperlioceras bicarinatum* (ZIETEN) = *Pseudopolyplocus bicarinatus* (ZIETEN), *Hildoceras semipolium* (BUCKM.); data from Imhof in Jordan (1983); ζ = data from Imhof in Jordan (1983)

Section Hof Horn (SO); coord.: 631.700 / 245.800

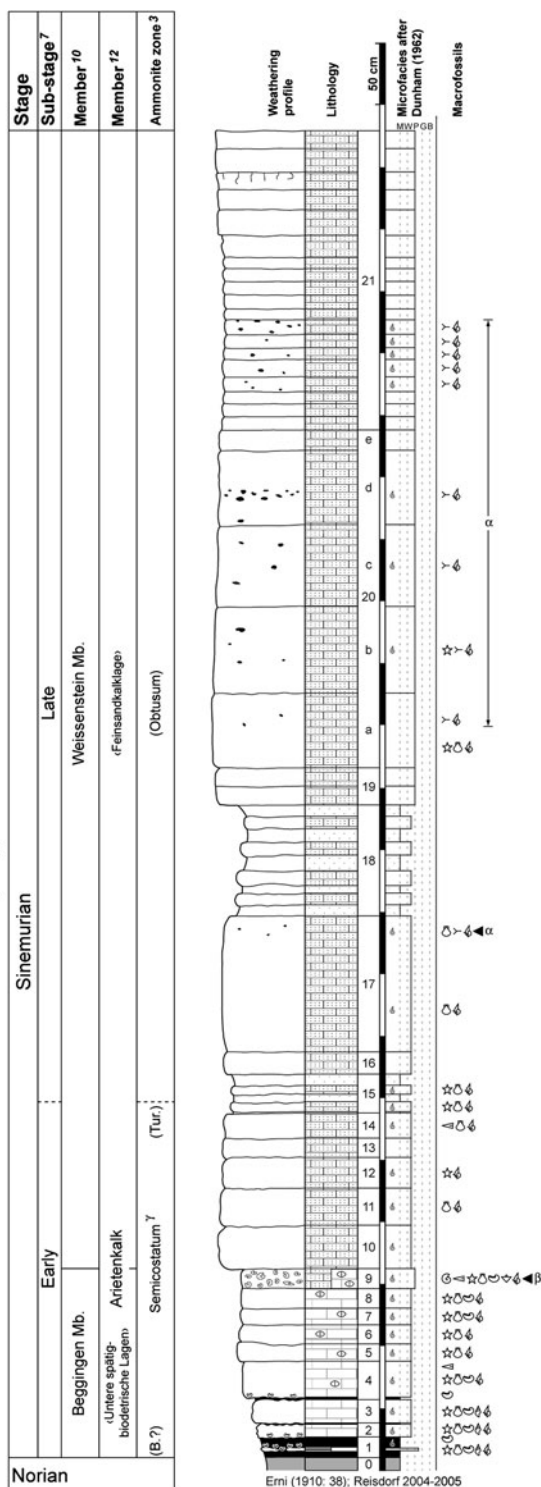


Fig. 14 Detailed section of the Early Jurassic strata at Hof Horn (NW Olten). α = whitish and bluish chert nodules (see also Moesch 1874; Buxtorf 1907; Fischer and Luterbacher 1963: 28); β = *Arnioceras* sp., *Arnioceras* cf. *cuneiforme* HYATT, *Arnioceras* cf. *robustum* (QUENST.); γ = *Coroniceras multicostatum* (SOW.), loosely collected

Underlying strata Beggingen Member or Weissenstein Member or Frick Member.

Overlying strata Breitenmatt Member.

Occurrence In the entire northern Swiss Folded Jura (except for the Mont Terri area) and areas south of the Folded Jura (i.e. Schafisheim borehole; Nagra 1992); in the eastern Folded Jura there is facies interfingering with the Frick Member; in the southern Jura chains this facies interfingers with the Weissenstein Member; facies interfingering with the Mont Terri Member has not been observed so far.

Thickness Up to ca. 27 m (Fig. 23).

Chronostratigraphic age Early Sinemurian to Early Pliensbachian (Semicostatum to Jamesoni zone; Jordan 1983; Schlatter 1991, 2000; Maisch and Reisdorf 2006a, b; own data).

Description The Fasiswald Member consists of alternating brown, light- to dark grey, quartz containing limestone, encrinite, silty-sandy terrigenous mudstone and marl, respectively (Figs. 10, 12, 13, 15, 16, 17, 18, 19, 20, 25; see Mühlberg 1908; Delhaes and Gerth 1912; Heim 1919). In the Hauenstein area and from there further to the west, and in the well Schafisheim (coord.: 653.620/246.760), limestone beds are silicified to a varying degree and may contain black chert-concretions which may reach a size of several tens of centimeters (*Spiculaefazies* of Jordan 1983; Figs. 15, 17, 18; see Delhaes and Gerth 1912; Nagra 1992; Maisch and Reisdorf 2006a). *Gryphaea obliqua* (Sow.) occurs in great abundance in the area of the Fasiswald Member (Figs. 15, 17; see Jordan 1983; Wetzel et al. 1993; Reisdorf 2001). Biostratigraphically useful macrofossils are, however, quite rare (Jordan 1983; Behr 2004; Reisdorf own data). As a rule, one to two packages of limestone beds several meters in thickness occur; they may appear as distinct ridges in the landscape (Jordan 1983). Especially in the Weissenstein area, the facies of the Fasiswald Member interfingers with the Weissenstein Member (Fig. 3; see also Fischer and Luterbacher 1963) while in the eastern Folded Jura, the Fasiswald Member overlies the Beggingen Member, Frick Member or the Weissenstein Member (Figs. 10, 12, 13, 15, 16; see Buxtorf 1907; Jordan 1983; Reisdorf 2001).

4.7 Mont Terri Member

Names previously in use are given in Figs. 2 and 4.

Type locality Les Salins (SE Courtemaury; canton Jura; coord.: 578.800/248.080; Fig. 26).

Underlying strata Beggingen Member.

◀ **Fig. 15** Detailed section of the Early Jurassic strata at Wirbligen (BL), temporary exposure; modified after Reisdorf (2001). α = compare Jordan (1983: section Dottenberg) and Fig. 12; Etzold et al. (1975), Schlatter (1983b, 1991), Brandt (1985); β = revision of “*Paltechioceras* s.l.”; γ = *Xiphoceras* sp. (revision of “*Apoderoceras* sp.”; loosely collected)

Overlying strata Breitenmatt Member.

Occurrence Mont Terri area.

Thickness Up to ca. 25 m thick (Buxtorf 1910; Laubscher 1963).

Chronostratigraphic age Late Sinemurian to Early Pliensbachian (?Obtusum to Davoei zone; own data).

Description Middle to dark grey mica bearing terrigenous mudstone and marl with occasional nodular to compact limestone layers are characteristic (Fig. 26; Buxtorf 1910; Glauser 1936; Rickenbach 1947). This member is only rare exposed entirely. According to Buxtorf (1910) and Laubscher (1963) it starts with terrigenous mudstone, which successively changes into a limestone-marl-alternation. The general appearance of the Mont Terri Member resembles therefore the gradual dovetailing of facies of the Frick Member with the Fasiswald Member in the eastern Folded Jura (compare Figs. 10, 15, 16, 19; Pratje 1924; Jordan 1983; Wetzel et al. 1993; Bath and Gautschi 2003).

In spite of their macroscopic similarity, the stratigraphic architecture and the lithological inventory of the Mont Terri Member markedly differ from those of both the Frick Member and the Fasiswald Member. Lithologically, these differences in facies in the Mont Terri area are so pronounced that they should not be seen as mere facial variations. As explained in greater detail below, the character of the Mont Terri Member can be boiled down to the following: The Mont Terri Member stands out, not by dint of its having a unique stratigraphic architecture or a unique lithological inventory, but in fact due to the very lack of such unique qualities.

Buxtorf (1910) measured a 10–12 m thick terrigenous mudstone interval (= *Obtusum* sensu Buxtorf 1910, Fig. 2) in a temporary exposure SE of Cornol (coord.: ca. 580.550/249.100). This succession is assigned to the here newly introduced basis of the Mont Terri Member (Fig. 3). This mudstone most closely resembles the easternmost occurrences of the Frick Member in the Folded Jura with respect to facies, although it is significantly thicker than the latter (compare section Buessge, Fig. 10; see Jordan 1983; Bath and Gautschi 2003). The more western occurrences of the Frick Member differ more clearly from the basal interval of the Mont Terri Member. More frequent interfingering of the Frick Member with the Fasiswald Member in this area leads to the characteristic broadening of the lithological inventory of the Frick Member, in particular

the occurrence of crinoidal mudstone and wackestones as well as one to two prominent *Gryphaea*-rich intervals (*Gryphäenkonglomerathorizonte* after Jordan 1983; Wetzel et al. 1993). Judging by the information in Buxtorf (1910), the latter seems to be absent in the basal part of the Mont Terri Member (see also Vonderschmitt 1942).

The upper part of the Mont Terri Member (= *knollige Kalkbänke* after Buxtorf 1910; Laubscher 1963; Fig. 4) resembles the Fasiswald Member: In the type section Les Salins (Fig. 26), this limestone-marl-alternation is about 13 m thick and does not exhibit the characteristic lithological inventory of the Fasiswald Member, namely calcarenites in spiculae-facies or without spiculae, encrinurites linked to *Gryphaea*-rich intervals, as well as one to two packages of limestone beds several meters in thickness.

The biostratigraphic range of the Mont Terri Member is not completely clear yet and is based on the current knowledge of unexpectedly heterogeneous stratigraphic features (Fig. 3). Hitherto, ammonites are only known from the limestone-marl-alternation of the Mont Terri Member (own data; cf. Mathey 1883). In the type section Les Salins (Fig. 26) as well as in the tectonically overprinted partial section S of Cornol (coord.: 579.950/249.500; *Aegoceras* sp., ?*Oistoceras* sp., own data) and SSW of Courtemaury (coord.: 578.100/248.050; *Echioceras* sp.; *Aegoceras* sp., own data), ammonite finds document the *Raricostatum* and *Davoei* zones for this stratigraphic level and therefore indicate that deposition continued to the late Early Pliensbachian (Fig. 3).

The stratigraphic position of the Sinemurian/Pliensbachian boundary could not be identified precisely in the type section of the Mont Terri Member (Fig. 26). The above mentioned partial section SSW Courtemaury, however, yielded a precise localisation of the biostratigraphic boundary. In that partial section, the oldest sediments of the Pliensbachian (*Jamesoni* and *Ibex* zones) in the Mont Terri area are rather thin: here, *Echioceras* sp. (*Raricostatum* zone) and *Aegoceras* sp. (*Davoei* zone) occur in close proximity in a monotonous interval consisting of marls and a few nodular limestones or limestone beds. These limestones can be classified as mudstones to wackestones.

The stratigraphic constellation exposed in the partial section of SSW of Courtemaury (Fig. 26) suggests that neither the Sinemurian-/Pliensbachian-boundary nor the *Ibex*/*Davoei* zone-boundary can be found in a belemnite- and gryphaeid-rich wackestone to packstone or phosphoric limestone/marl-alternation in the area where the Mont Terri Member is present (compare Breitenmatt Member; see Jordan 1983; Maisch and Reisdorf 2006a, b). This definition of the boundary, however, conflicts with the situation in the Courtemaury section (Fig. 27), which lies about 500 m southwest of the type section Les Salins and which, for the most part, represents the Beggingen Member.

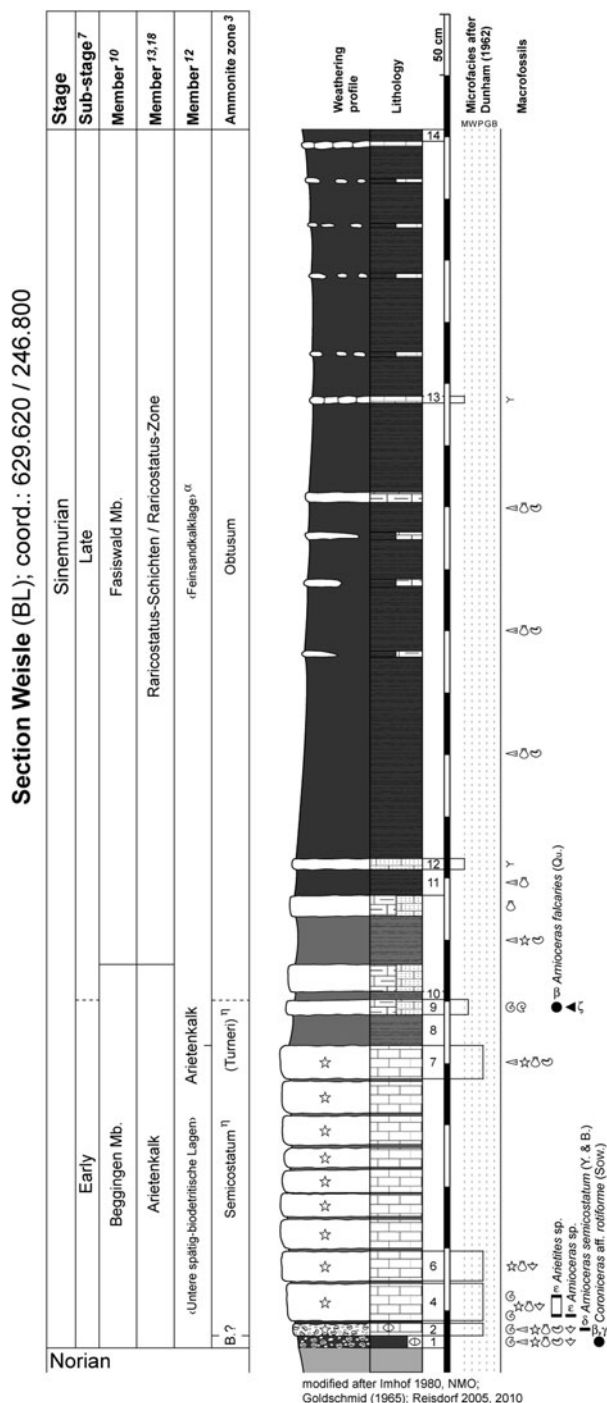


Fig. 16 continued

closer examination of the section of Courtemaury yielded no distinct evidence for a tectonic overprint by folding or thrusting.

Based on the available bio- and lithostratigraphical data from the study area, two differing possible positions of the boundary between the Beggingen Member and the

Mont Terri Member are shown in the stratigraphic scheme of the Staffelegg Formation (Fig. 3). In the eastern Mont Terri region, the position of this boundary is purely based on lithostratigraphic correlation with areas to the eastern Folded Jura (= boundary within the Obtusum zone; Fig. 3).

Based on the section Courtemaury, the proposed boundary differs significantly from that of the traditional stratigraphic nomenclature: for the western Mont Terri area, the boundary is set at a diachronous erosional base that reaches from the Ibex zone to the Bucklandi zone (cf. Frank 1926: 404; Söll 1965: 157; Kant 1972: 29).

4.8 Breitenmatt Member

Names previously in use are given in Figs. 2 and 4.

Type locality Breitenmatt (ESE Gansingen; canton Aargau; coord.: 654.040/265.280; Buser 1952; outcrop no longer accessible).

Underlying strata Grünschholz Member or Fasiswald Member or Mont Terri Member.

Overlying strata Rickenbach Member or Rietheim Member or Gross Wolf Member (Erlimoos Bed).

Subdivision Trasadingen Bed and Müsenegg Bed.

Occurrence Northern Switzerland.

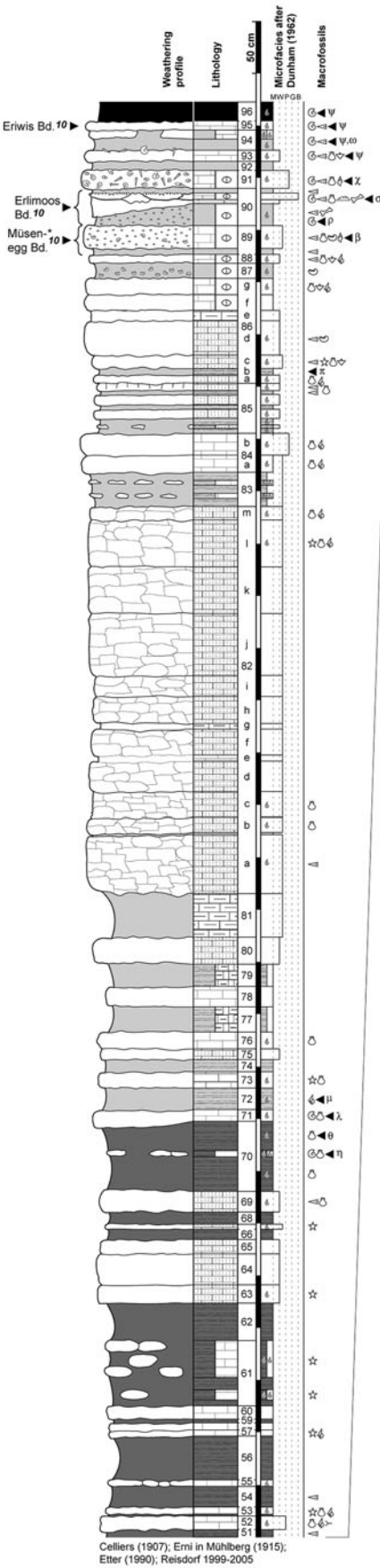
Thickness Smallest thickness of ± 50 cm in the Tabular Jura and the Klettgau area (Fig. 9; Schälch 1880: 225; Buxtorf 1901: 21; Buser 1952: 61p.); thickest occurrences together with the Müsenegg Bed (± 4 m in the Weissenstein area; Buxtorf 1907); without the Müsenegg Bed the thickness can still be well above 2 m (maximum of 2.8 m in the Klettgau area; Hofmann 1981). In the Mont Terri area, the Breitenmatt Member is ca. 1.7 m thick.

Chronostratigraphic age Early to Late Pliensbachian (Jamesoni to Spinatum zone; Jordan 1983; Schlatter 1991, 2000; Maisch and Reisdorf 2006a, b).

Description Interval rich in fossils, consisting of marls and phosphoritic, predominantly concretionary limestones; belemnites and gryphaeid oysters dominate the macrofauna; presence of ichnofossils results in a spotted appearance (Figs. 7, 9, 10, 12, 13, 15, 16, 17, 18, 19, 20, 26; see Braun 1920; Glauser 1936; Rickenbach 1947; Gsell 1968; Schlatter 1991). Belemnite-rich (so-called belemnite battlefields) horizons of Early Pliensbachian age containing glauconite can provide a strong gamma-log signal (Nagra 1984, 1990, 2001). Partial silicification of calcareous fossils is also often seen (especially in gryphaeid oysters; e.g., Mandy 1907; Jordan 1983).

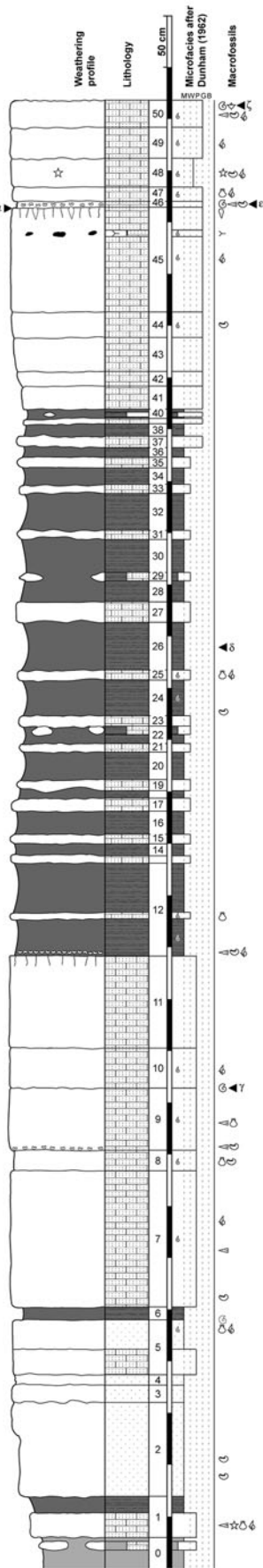
Section Fasiswald (Hägendorf/ SO); coord.: 628.800 / 245.100

Sinemurian			Toarcian		A. Stage		
Late			Late		Sub-stage ⁷		
			Early	L.	Member ¹⁰	Member ^{12**}	
Obtulum-Schichten ^α	Grammocythere acclivulcata	Fasiswald Mb.	Breitenmatt Mb.		Gross Wolf Mb.	O. T. ¹⁷	
			Upton-Sch.	Könd. Plens.	V. H.	Jurensis-Mergel	
		Obliqua-Schichten		no stratigraphical subdivision			
		Obliqua-Schichten		no stratigraphical subdivision			
Raricostatum			J.	M./Ibex?	S.	T.	
					Ostracod zone ⁶		
					Ammonite zone ⁵		



Celliers (1907); Erni in Mühlig (1915);
Etter (1990); Reisdorf 1999-2005

Sinemurian				Stage
Early		Late		Sub-stage ⁷
Facies transition Beggingen Mb./ Weissenstein Mb.				Member ¹⁰
„U. sp. b. L.“	Arietenkalk	«Feinsandkalklage»	Arietenkalk ^α	Obtulum-Sch. ^α <small>(Obere spaltig- biotritische Lagen)</small>
	no stratigraphical subdivision		Anchistrocheilus? tuniungensis n. sp.	
(B.)	Semicostatum	(Tur.)	Obtulum	Ostracod zone ⁶
				Ammonite zone ⁵ (Oxyptotum?)



◀ **Fig. 17** Detailed section of the Early Jurassic strata at the Fasiswald clay pit (W Olten). α = compare Jordan (1983: section Dottenberg) and Fig. 12; see also Etzold et al. (1975); Schlatter (1983b, 1991); Brandt (1985); β = “0.15 m Grauer Kalk, *Gryphaea cymbium*” of Celliers (1907: 17); see also Delhaes and Gerth (1912); γ = *Microderoceras* sp. (own data); δ = ostracods (own data, det. E. Beher 2004): *Anchistrocheles? tuningensis* BEHER, *Bairdia molesta*; ε = *Asteroceras* sp. (reworked?, own data, compare Schlatter 1983b; finder: C.A. Meyer, Basel 2009); ζ = *Aegasteroceras* gr. *simile* SPATH (own data, biostratigraphic range according to Schlatter 1983b, 1991); η = *Echioceras* s.l. (own data); θ = ostracods (own data, det. E. Beher 2004): *Acrocythere oeresundensis*, *Acrocythere michelseni*, *Bairdia molesta*, *Bairdia? extracta*, *Cytherelloidea modesta*, *Grammannicythere acclivisulcata*, *Gammacythere ubiquita*, *Isobryhocypis tatei*, *Ledahia* sp., *Ogmoconcha amalthei*; λ = *?Echioceras* s.l. (own data); μ = ostracods (own data, det. E. Beher 2004): *Acrocythere oeresundensis*, *Bairdia molesta*, *Bairdia praehilda*, *Cardobairdia liassica*, *Cuneoceratina amlingstadtensis*, *Cytherella* sp., *Cytherelloidea lacertosa*, *Gammacythere ubiquita*, *Isobryhocypis tatei*, *Ledahia bispinosa*, *Nanacythere* sp., *Ogmoconcha amalthei*, *Ogmoconchella* sp. 1 (Beher 2004), *Polycopse* sp.; π = ostracods (own data, det. E. Beher 2004): *Cytherelloidea modesta*, *Ledahia bispinosa*, *Progonioidea auleata*; ρ = *Lytoceras* sp., *Liparoceras* (*Parinodicerus*) gr. *zieteni* (TRUEMAN), *Aegoceras* sp., *Derolytoceras* sp. (own data); σ = *Lytoceras* sp.; χ = *Lytoceras* sp., *Liparoceras* sp., *Haugia* sp.? (own data; see also Erni in Mühlberg 1915); ψ = faunal list in Etter (1990); ω = *Lytoceras* sp., *Grammoceras* (gr. *fallaciosum*) sp. (own data); * = in the Fasiswald section, the Müsenegg Bed can even be completely eroded (see Erni in Mühlberg 1915); ** = see also Erni in Mühlberg (1915)

Distinct hardgrounds are sometimes developed in the Breitenmatt Member (Jordan 1983; Müller et al. 1984; Nagra 1992; Wetzel et al. 1993). In general, the Breitenmatt Member is significantly thinner than age-equivalent sediments in southern Germany and eastern France (see Vonderschmitt 1942; Gwinner et al. 1967: Table 1; Wirth 1968; Etzold et al. 1975; Debrand-Passard 1984). In the Mont Terri area, the facies of the Breitenmatt Member is limited to the Davoei zone, including a thin phosphoritic interval that has been attributed to the Mont Terri Member by Jordan et al. (2008: fig. 14.31). However, in the remaining study area, the Breitenmatt Member represents a highly condensed interval that, together with the Müsenegg Bed, can span all the ammonite-zones of the Pliensbachian (Fig. 3; see Pratje 1924; Schlatter 1991; Wetzel and Reisdorf 2007). In addition, the Breitenmatt Member has been exposed to pronounced synsedimentary and postsedimentary erosion and reworking processes (see Müller et al. 1984; Brandt 1985; Schlatter 1991). It's biostratigraphical extent is therefore only incompletely preserved, especially in the Folded Jura (Figs. 3, 19 and 20; Schlatter 1991; Wetzel et al. 1993).

4.8.1 Trasadingen Bed

Names previously in use are given in Fig. 4.

Type locality A now filled up pit 200 m SW of Trasadingen (Kilchstieg, canton Schaffhausen; coord.: 674.100/280.050; Schalch 1880).

Underlying strata The Trasadingen Bed represents the uppermost bed of the Breitenmatt Member in the Tabular Jura and the Klettgau area.

Overlying strata Rickenbach Member.

Occurrence Klettgau area, Zürcher Weinland, Tabular Jura, ?Mont Terri area.

Thickness Up to 30 cm (Fig. 7).

Chronostratigraphic age Early Pliensbachian (Davoei zone, Davoei and Oistoceras subzones; Schlatter 1991).

Description Middle grey, splintery marly limestone which has a spotted appearance because of their burrows (Figs. 7 and 9; Schalch 1880, 1916; Schlatter 1991). This most conspicuous lithostratigraphic horizon of the Breitenmatt Member wedges out laterally and passes into a calcareous marl (see Brändlin 1911; Schlatter 1991). In the study area, the biostratigraphy of this bed correlates with the first and last occurrence of the ammonite *Prodactylioceras davoei* (Sow.) within a limestone layer (see Brändlin 1911; Schlatter 1991; see also Fig. 26).

4.8.2 Müsenegg Bed

Names previously in use are given in Figs. 2 and 4.

Type locality Müsenegg (S Schinznach; canton Aargau; coord.: 652.570/253.350; Jordan 1983).

Underlying strata The Müsenegg Bed represents the uppermost bed of the Breitenmatt Member in the Folded Jura, except in the Mont Terri area.

Overlying strata Rietheim Member or Gross Wolf Member.

Occurrence Folded Jura (except for the Mont Terri area).

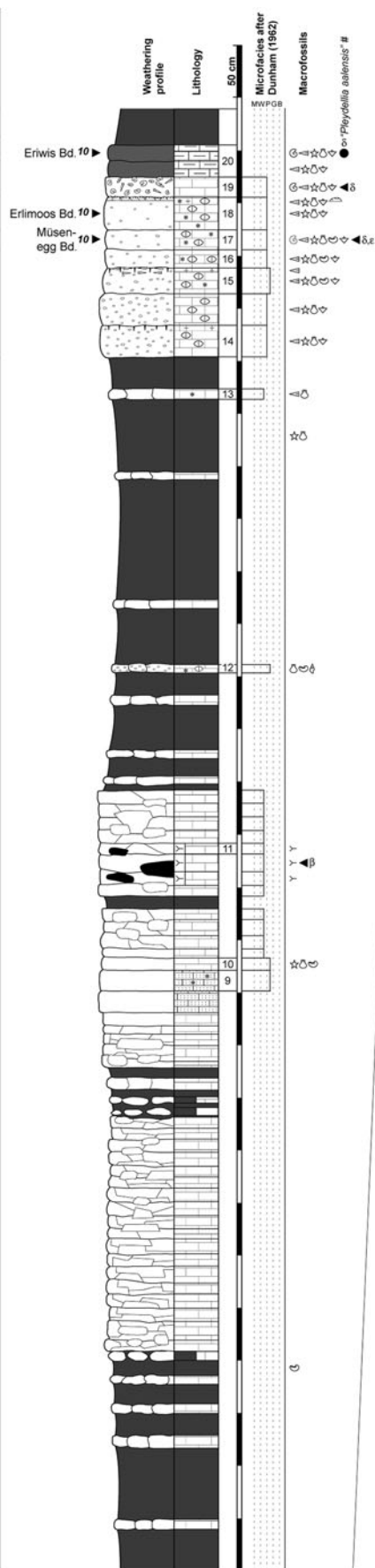
Thickness From 0 to 70 cm thick (Figs. 17, 19, 23).

Chronostratigraphic age Late Pliensbachian (Margaritatus to Spinatum zone; Fig. 18; see Buxtorf 1907; Hess 1962; Jordan 1983; Maisch and Reisdorf 2006a, b).

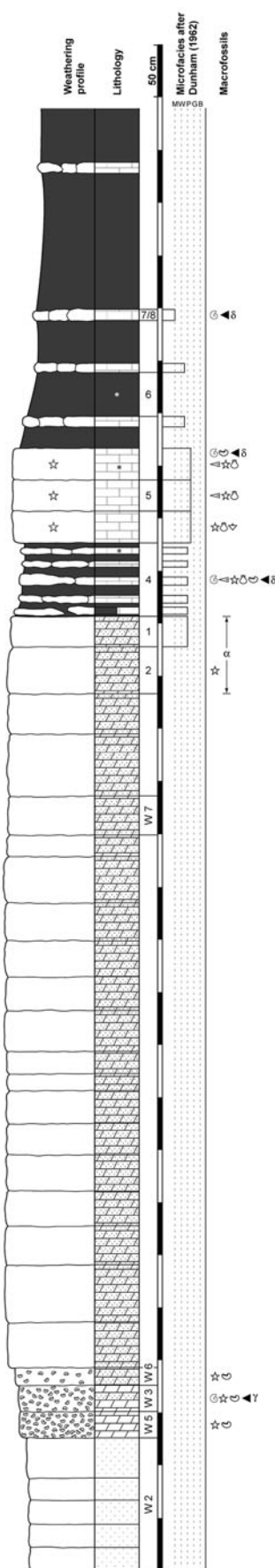
Description Condensed phosphoritic marl and/or one marly limestone bed (Figs. 10, 11, 13, 15, 16, 17, 21, 23). The Müsenegg Bed can be capped by a hardground (Figs. 13, 23; Wetzel et al. 1993). The distinct, irregular light to dark grey spotted appearance of the Müsenegg Bed is characteristic; it is caused by the diverse ichnofauna occurring in these strata (Jordan 1983; Wetzel and Reisdorf 2007). Bivalves of the genus *Gryphaea* are the most conspicuous component of the macrofauna (see Erlimoos Bed).

Therefore, the petrography of the Müsenegg Bed is sometimes difficult to differentiate from that of older layers

Sinemurian	Pliensbachian		Toarcian		A. Stage
	Early	Late	E.	Sub-stage ⁷	
Fasisswald Mb.	Breitenmatt Mb.	Gross Wolf Mb. O.T.	¹⁷	Member ¹⁰	
Gryphitenkalke des Unteren Lias	Mittlerer Lias	Oberer Lias	D.	Subdivision ⁸	
Obliqueschichten	Belemnitenkalk	Jurensis-Mergel	O.T.	Member ⁸	
	(J., Ilex, Darvexi)	(M., y S)	T.	L. (O.)	
(Raricostatum)				Ammonite zone 3	



Middle Rhaetian	Sinemurian			Stage
	Early		Late	Sub-stage ⁷
	Beggingen Mb.	Weissenstein Mb.	Fassiswald Mb.	Member ¹⁰
	Gryphitenkalke des Unteren Lias			Subdivision ⁸
	Arcuata-schichten	Obliqueschichten		Member ⁸
	Semicostatum	(Turner)	(Obolusum)	(Oxynotum?) Ammonite zone 3 (Raricostatum)



◀ **Fig. 18** Detailed section of the Late Triassic and Early Jurassic strata at Chuenisrüti and Wuest (BL). α = *Obtusussandsteine* after Buxtorf (1907); β = see also Delhaes and Gerth (1912); compare Figs. 13, 15, 16; γ = “*Arietites*” (Erni 1910, 1926); δ = data from Imhof in Jordan (1983); compare Etzold et al. (1975), Schlatter (1983b, 1991) and Brandt (1985); ε = “*Amaltheus costatus*” (approximate stratigraphic position after Delhaes and Gerth 1912)

of the Breitenmatt Member. In such case, a certain stratigraphic classification can only be achieved with index fossils of the Late Pliensbachian. The biostratigraphically orderless appearance of index fossils like ammonites, foraminifers and ostracods indicates substantial reworking and bioturbation during the deposition of the Müsenegg Bed (Hess 1962; Jordan 1983; Wetzell and Reisdorf 2007).

4.9 Rickenbach Member

Names previously in use are given in Figs. 2 and 4.

Type locality 700 m NNE of Rickenbach (“Hintern Egg” = Waldegg, canton Baselland; coord.: 631.180/260.320; Buxtorf 1901; the section is not accessible at the present time).

Underlying strata Breitenmatt Member.

Overlying strata Rietheim Member (Schlatter 1982; cf. Joachim 1970: 16; Etzold et al. 1975).

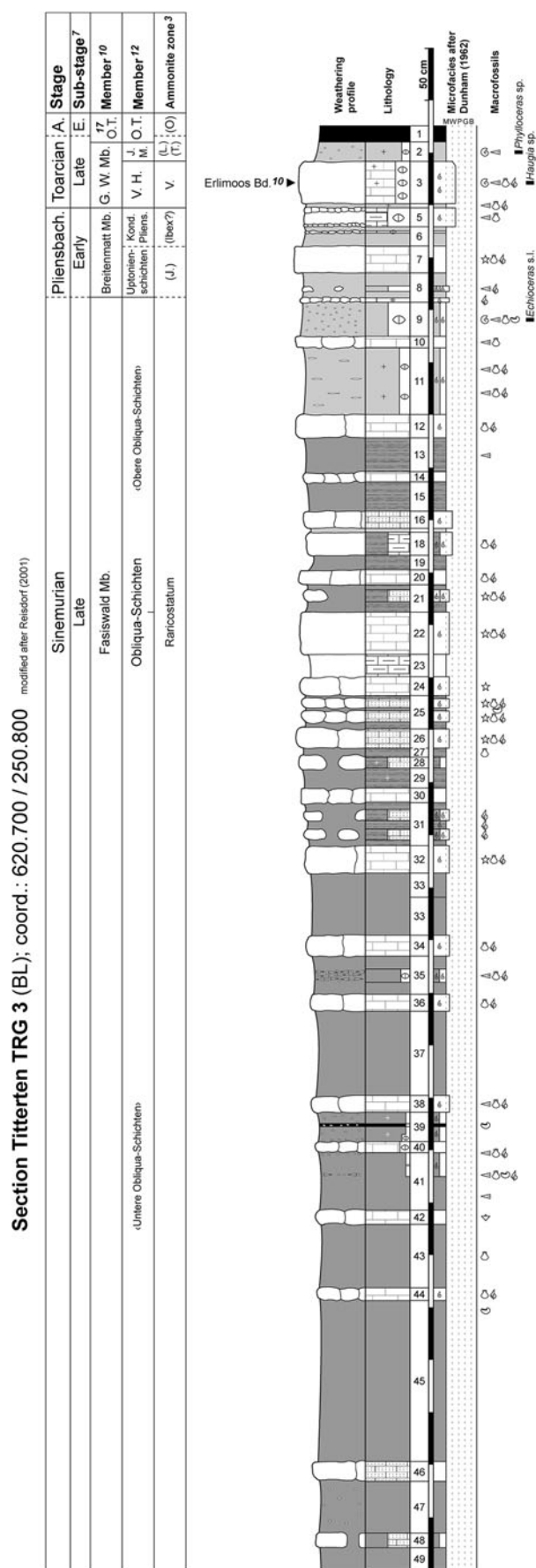
Occurrence Klettgau area, Zürcher Weinland, Tabular Jura, ?Bernese Jura (Elber 1921), ?Mont Terri area (Fig. 26).

Thickness In the Tabular Jura, minimal thicknesses are probably around 25 cm (Nagra 1990); the questionable Rickenbach Member in the Mont Terri area is also only a few decimeters thick (Fig. 26; see Glauser 1936; Bitterli 1960); maximum thickness is significantly above 5 m in the Klettgau area (Schalch 1880; possibly up to ca. 10 m?, Hofmann 1981); in the Tabular Jura, thickness of around 2 m is observed (see Buxtorf 1901).

Chronostratigraphic age Late Pliensbachian to Early Toarcian (Margaritatus to Tenuicostatum zone, Stokesi to Paltum subzone; Figs. 7, 9; Schlatter 1982, 1985: 13, 1991).

Description Condensed interval of reduced thickness (except in the northern Klettgau area; see Schalch 1916; Gsell 1968; Nagra 2001 and references therein), consisting of glauconitic, phosphoritic, fossil-rich (especially rich in belemnites; so-called belemnite battlefields) marls and concretionary limestones (Figs. 7, 9, 26; see Brändlin 1911; Pratje 1924; Buser 1952). At the top of the

Fig. 19 Detailed section of the Early Jurassic strata at Titterten TRG ▶ 3 (BL), temporary exposure; modified after Reisdorf (2001)



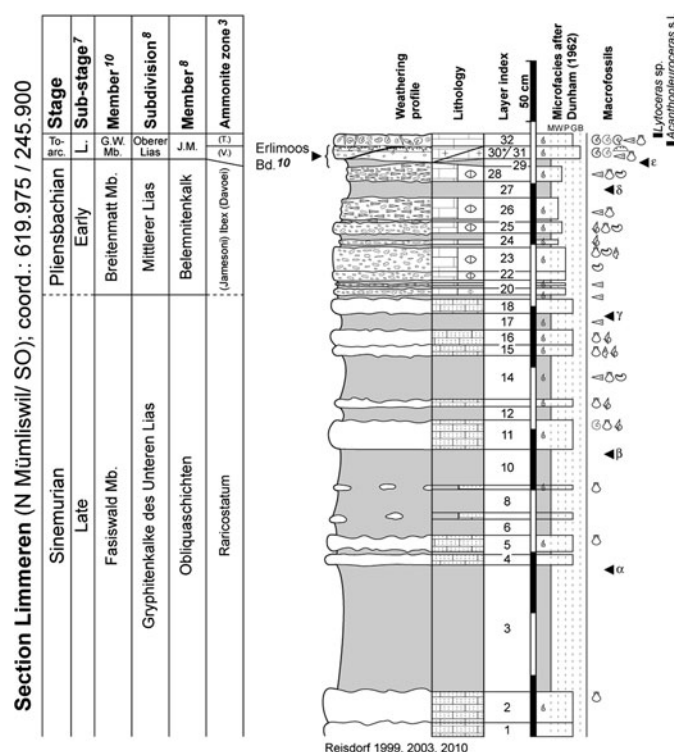


Fig. 20 Detailed section of the Early Jurassic strata at Limmeren (N Mümliswil/SO; see section “Limmernbach SW Ramisgraben”, Delhaes and Gerth 1912). α = ostracods (own data, det. E. Beher 2004; for the stratigraphic range of the ostracods see Beher 2004 and Franz et al. 2009); *Acrocythere michelseni*, *A. oeresundensis*, *Gramannicythere acclivisulcata*, *Gramannicythere* sp. 1; β = ostracods (own data, det. E. Beher 2004); *Ektypocythere vitiosa*, *Gramannicythere acclivisulcata*; γ = ostracods (own data, det.

E. Beher 2004); *Bythocypris postera*, *Cytherelloidea lacertosa*, *C. modesta*, *Gammacythere ubiquita*, *Liasina vestibulifera*, *Ogmoconcha amalthei*; δ = ostracods (own data, det. E. Beher 2004); *Bairdia molesta*, *Cardobairdia* sp. 1 BEHER, *Ogmoconcha amalthei*; ε = ostracods (own data, det. E. Beher 2004); *Kinkelinella sermoisensis*, *Ledahia bispinosa*, *L. mouherense*, *Ogmoconcha* sp., *Paracypris* sp. (semidisca?); * = note the erosional unconformity between beds 30 and 31

Rickenbach Member, bluish grey marls (= *Blaugraue Mergel* sensu Schlatter 1982) can be found in the Klettgau area and in the Tabular Jura, greenish grey to blackish grey clayey marls occur (= *Basisschicht* of Kuhn and Etter 1994; Fig. 7), both in small thicknesses.

4.10 Rietheim Member

Names previously in use are given in Figs. 2 and 4.

Type locality Rietheim (canton Aargau; coord.: 662.910/271.865; outcrop in the bed of a stream; see Kuhn and Etter 1994).

Underlying strata Rickenbach Member or Breitenmatt Member.

Overlying strata Gross Wolf Member.

Subdivision Unterer Stein.

Occurrence Klettgau area, Zürcher Weinland, Tabular Jura, eastern Folded Jura to Hauenstein area, Weissenstein area, Bernese Jura, Mont Terri area.

Thickness The thickness of about 10 m in the Klettgau area decreases towards the south and southwest (Tabular Jura and Folded Jura) markedly to a few centimetres (see Elber 1921; Riegraf 1985: 62; Kuhn and Etter 1994; Nagra 2001; Reisdorf 2001). By contrast, the Rietheim Member attains a thickness of some 20 m in the Mont Terri area (Fig. 26; Rickenbach 1947; Bitterli 1960; Contini and Lamaud 1978). Additionally, the Rietheim Member does not occur areawide in the Folded Jura due to erosion (Figs. 13, 15 16, 17, 18, 19, 20, 21, 23; see Erlimoos Bed; see Kuhn and Etter 1994; Reisdorf 2001).

Chronostratigraphic age Early Toarcian (Tenuicostatum to Bifrons zone, Paltum to Crassum subzone; Schlatter 1982; Richter 1987; Kuhn and Etter 1994; Maisch and Reisdorf 2006a, b).

Description Bituminous, predominantly thinly bedded shale and marl layers which can be clearly separated from the under- and overlying members by their brownish, dark grey to black colour (Figs. 7, 9 10, 11, 26; see Bitterli 1960; Richter 1987; Kuhn and Etter 1994; Nagra 2001). Thin limestone beds and calcareous concretions occur in

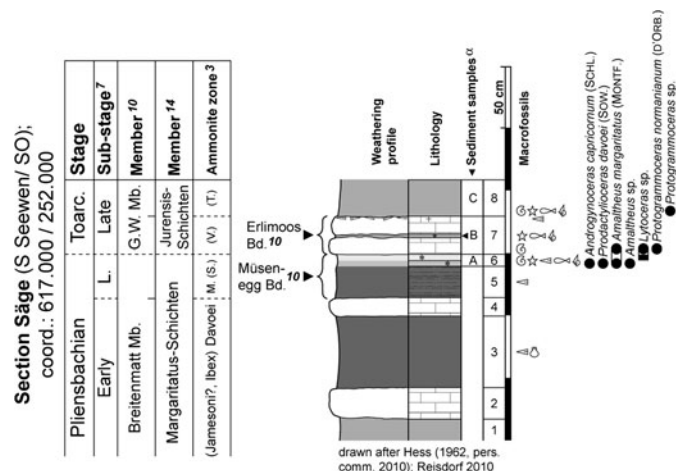


Fig. 21 Detailed section of the Early Jurassic strata at Säge (S Seewen/SO), drawn after Hess (1962, pers. comm. 2010). α = (A, B, C) faunal list of the ostracod and foraminiferal assemblages in Hess

(1962), compare Rieggraf (1985); see also Bitterli (1960), Richter (1987) and Tröster (1987)

addition in the Rietheim Member (Figs. 7, 10, 11, 26; see Senftleben 1923; Pratje 1924; Kuhn and Etter 1994; Nagra 2001). These are prominent in thin Early Toarcian sections. Where the Rietheim Member reaches large thickness (Klettgau area, Mont Terri area), the limestone beds are outweighed by siliciclastic sediments.

Some of the limestone beds are important lithostratigraphic markers that can be correlated as far as France and southwestern Germany (cf. Rieggraf et al. 1984: 14p.; Kuhn and Etter 1994; Röhl et al. 2001). The most important marker bed for the Early Toarcian in northern Switzerland, the Unterer Stein, is usually developed even the Rietheim Member is very thin (Fig. 9; see Buxtorf 1907; Elber 1921; Vogel 1934; Jordan 1983).

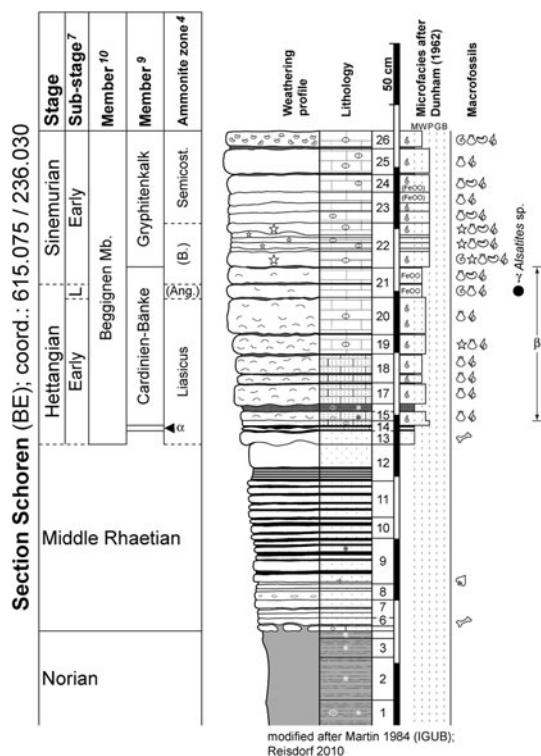


Fig. 22 Detailed section of the Late Triassic and Early Jurassic strata at Schoren (BE). α = "Insektenmergel" (compare Fig. 24); β = beds rich in *Plagiostoma* (Rollier 1910); γ = reworked? (see Schloz 1972; Schlatter 1988 and Fig. 7)

4.10.1 Unterer Stein (in the rank of a bed)

Names previously in use are given in Fig. 4.

Type locality Bad Boll (SSW Göppingen, southern Germany; Oppel 1856–1858).

Occurrence Klettgau area, Zürcher Weinland, Tabular Jura (may wedge out laterally in the Basel Tabular Jura), eastern Folded Jura to the Hauenstein area, Bernese Jura, Weissenstein area, Mont Terri area.

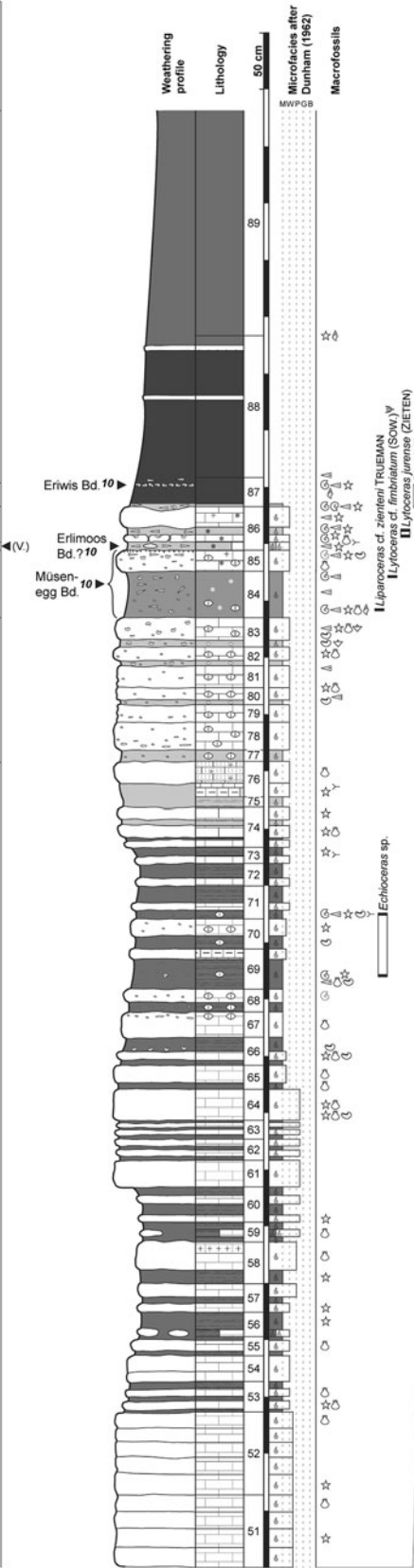
Thickness 0 up to 25 cm (e.g., Kuhn and Etter 1994; Maisch and Reisdorf 2006a, b), in the Mont Terri area roughly twice as thick (e.g., Rickenbach 1947).

Chronostratigraphic age Early Toarcian (Falcifer zone, Exaratum subzone; Kuhn and Etter 1994; Röhl et al. 2001).

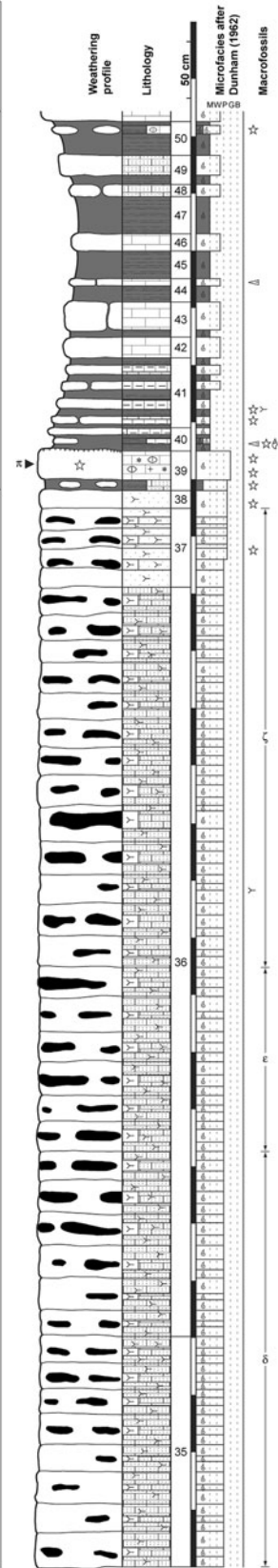
Description As a rule, the Untere Stein (= *erster Stinkstein*; von Wurstemberger 1876) is included in the basal layer interval of the Rietheim Member (Figs. 7, 9 10, 11, 26; e.g., Elber 1921; Pratje 1924; Kuhn and Etter 1994). It may also represent the basal layer of the Rietheim Member (e.g., in the Weissenstein area; Buxtorf 1907; Vogel 1934) and/or its topmost bed, for instance in the eastern Folded Jura (Jordan 1983). It is a distinct, bituminous limestone

Section Lucheren (BE); coord.: 614.820 / 236.235

Sinemurian		Toarc.		Stage
Late	Pliensbachian	Late	Aalenian	
Fasiswald Mb.	Early	Late	Early	Sub-stage ⁷
	Breitenmatt Mb.			
Obliqua-Schichten	Amaltheen-Schichten	Gross Wolf Mb.	Opalinus-Ton ¹⁷	Member ¹⁰
		Oberer Lias	Dogger	Subdivision ⁹
		Jurensis-Schichten	Opalinustone	Member ⁹
Raricostatum	(Jamesoni) Ilex (Davoei)	T. L.	(Opalinum)	Ammonite zone ⁴



Sinemurian		Stage
Late	Late	
Facies transition Fasiswald Mb. / Weissenstein Mb.	Fasiswald Mb.	Sub-stage ⁷
Unterer Lias (ohne Gryphaea obliqua-Schichten)	Mittlerer Lias (inkl. Gryphaea obliqua-Schichten)	Subdivision ⁹
Gryphitenkalk (Oberer Teil)	Obliqua-Schichten	Member ⁹
(Obtulum)	(Oxyotum?)	Ammonite zone ⁴



◀ **Fig. 23** Detailed section of the Early Jurassic strata at Lucheren (BE). α = beds rich in *Plagiostoma* (Rollier 1910); β = bluish chert nodules (see also Buxtorf 1907; Fischer and Luterbacher 1963 = 28); γ = whitish chert nodules; δ = bluish and grey chert nodules; ε = greyish black chert nodules; ζ = bluish and grey to dark grey chert nodules; π = compare Figs. 12, 13, 15, 16, 17, 18; ψ = for the biostratigraphic range of *Lytoceras* cf. *fimbriatum* (Sow.) see Schlatter (1991)

bed exhibiting clear lamination and having conchoidal-splintery fractures (Kuhn and Etter 1994; Etter and Kuhn 2000).

4.11 Gross Wolf Member

Names previously in use are given in Figs. 2 and 4.

Type locality Gross Wolf clay pit (canton Aargau; coord.: 645.725/253.350; Jordan 1983).

Underlying strata Rietheim Member or Breitenmatt Member.

Overlying strata Opalinus-Ton.

Subdivision (1) The Gross Wolf Member has the Gipf Bed or the Erlimoos Bed, respectively, at the base. Which of these two basal layers that is developed is strongly dependent on the next lower member. (2) In the eastern Folded Jura, but also in the occurrences in the Molasse basin to the south, the Eriwis Bed forms the uppermost bed of the Gross Wolf Member (see Jordan 1983; Nagra 1992).

Occurrence Northern Switzerland.

Thickness The minimum thickness is ± 60 cm (eastern Folded Jura; Figs. 13, 16, 19); maximum thickness is around 5.3 m in the eastern Folded Jura and 6.1 m in the Molasse basin (Fig. 11; Jordan 1983; Nagra 2001; some 19 m in the Buix well?, Schmidt et al. 1924: 13).

Chronostratigraphic age Late Toarcian to Early Aalenian (Variabilis to Opalinum zone; Tröster 1987; Nagra 1989, 1990, 1992; Etter 1990; Maisch and Reisdorf 2006a, b).

Description Condensed interval consisting of grey phosphoritic marls and concretionary marly limestones with pyrite and abundant macrofossils (especially belemnites and ammonites; Figs. 9 10, 11, 12, 13, 15 16, 17, 18, 19, 20, 21; see Elber 1921; Vogel 1934; Tröster 1987; Reisdorf 2001). However, unlike the sediments of the Sinemurian and Pliensbachian, the Gross Wolf Member seems to be almost completely barren of gryphaeid oysters (Senftleben 1923: 22 mentions a possible exception). The fossil-rich basal and topmost beds of the Gross Wolf Member deserve special attention (= Gipf Bed or Erlimoos Bed respectively; Eriwis Bed). They are stratigraphic index beds in the study

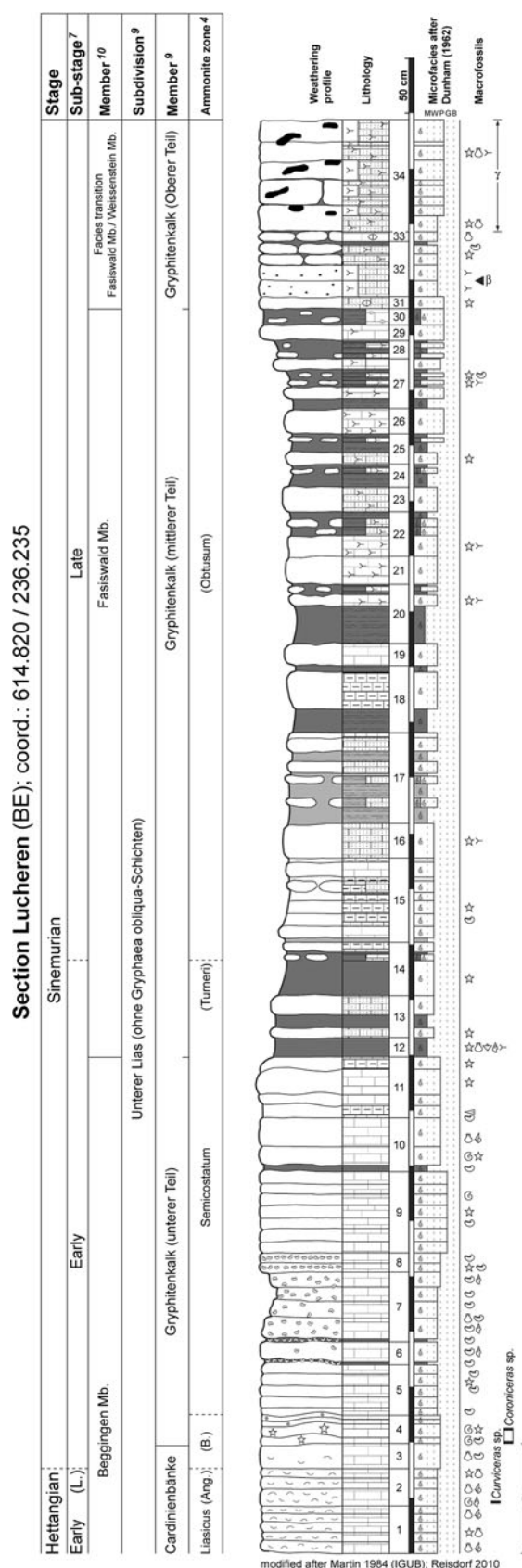


Fig. 23 continued

Section Käspisbergli (Günsberg; SO); coord.: 610.550 / 235.200

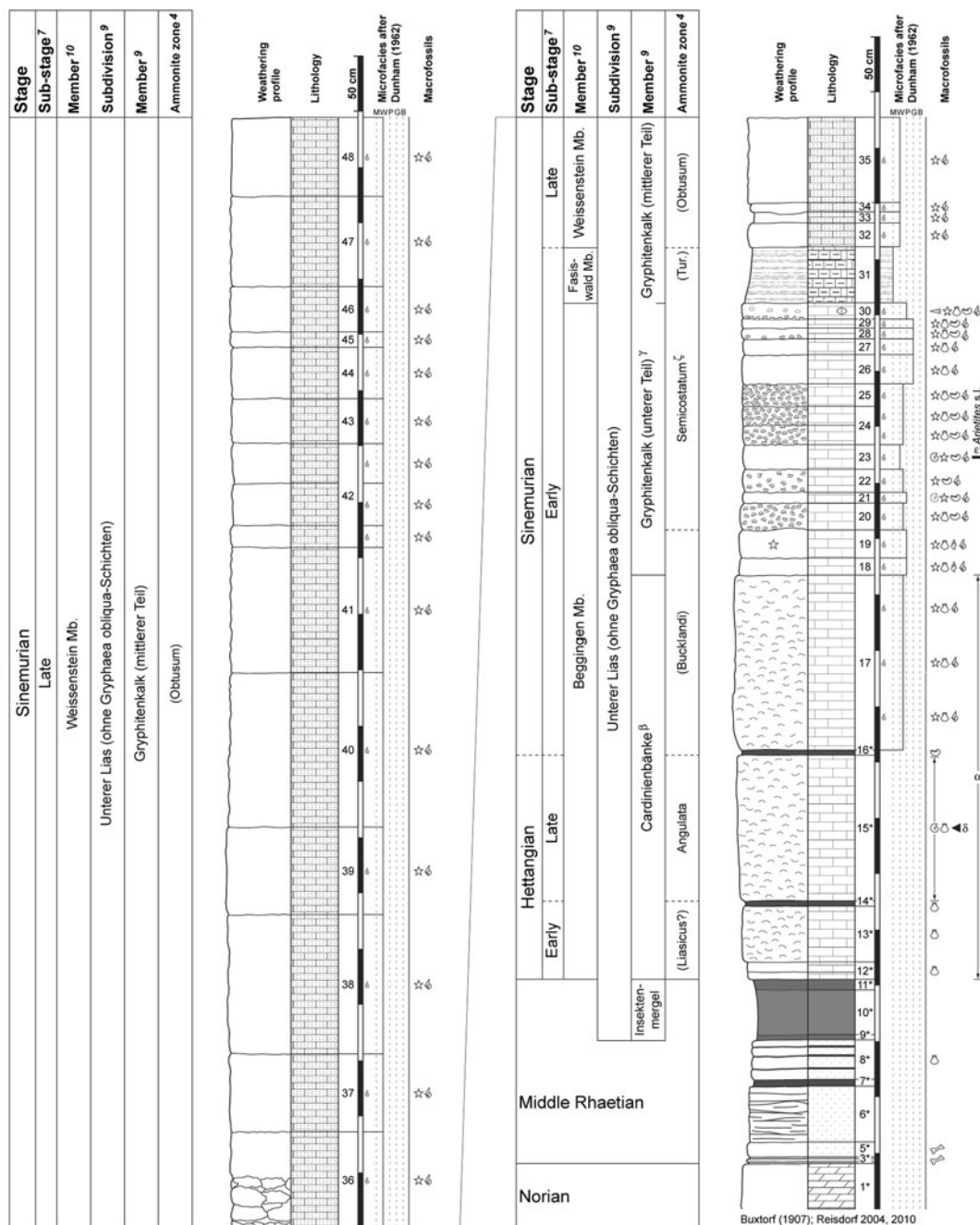


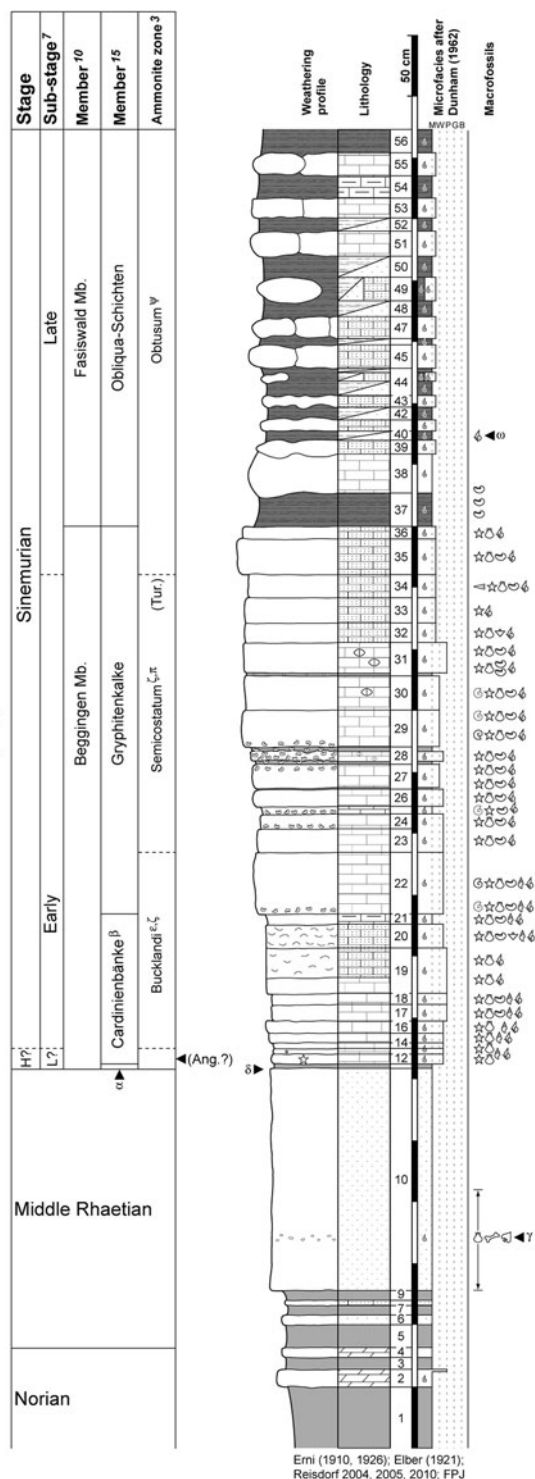
Fig. 24 Detailed section of the Late Triassic and Early Jurassic strata at Käspisbergli (Günsberg; SO). α = beds rich in *Plagiostoma* (Rollier 1910); β = “Grès à Cardinia, Gressly 1862” in Waagen (1864); γ = “Calcaire à Gryphées Gressly 1862” in Waagen (1864);

δ = “*Schlotheimia angulata*” (Buxtorf 1907); ε = see also Bitterli and Strub (1975); ζ = loosely collected: *Euagassicerias* sp. (own data); “*A. bisulcatus*” (see Waagen 1864); * = data from Buxtorf (1907)

area (see Jordan 1983; Nagra 1992; Kuhn and Etter 1994). Also, sediments of the Thouarsense zone have been observed, amalgamated in an ammonite- and belemnite-rich limestone bed in the thin occurrences in the Hauenstein—Passwang area (Figs. 13, 17, 18, 20; cf. Fischer 1964: 86p.; Etzold 1980; Riegraf et al. 1984: 61).

The boundary between the Gross Wolf Member and the Opalinus-Ton is not identical to the biostratigraphic boundary between the Early and Middle Jurassic. The latter can lie either within the Gross Wolf Member or within the Opalinus-Ton in northern Switzerland (see Nagra 1984, 1989, 1990; Etter 1990; Reisdorf et al. *subm.*; cf.

Section Hautes Roches (BE); coord.: 594.500 / 238.750



Franz and Nitsch 2009). The sedimentological expression of the boundary between these two stratigraphic units is mainly characterised by a sharp change in colour from predominantly grey marl in the Gross Wolf Member to dark grey to black mica-bearing, silty terrigenous mudstone in the Opalinus-Ton (see Etter 1990; Nagra 2001; Wetzel and Allia 2003).

◀ **Fig. 25** Detailed section of the Late Triassic and Early Jurassic strata at Hautes Roches (BE). ? = uncertain biostratigraphic affiliation (compare with Fig. 22); α = “*Insektenmergel*”? (compare with Fig. 22); β = see also Erni (1910, 1926) vs. Vollrath (1924: 22) and Frank (1930: 385); γ = see also Erni (1910, 1926) and Elber (1921); δ = loosely collected *Waehneroceras* sp. (= *Curvicerias*), reworked? (own data); ε = *Arietites* (*Arietites*) cf. *bisulcatus* (BRUGIÈRE), data from B. Hostettler (FPJ, 2005); ζ = *Coroniceras* sp. (loosely collected, own data); π = *Arnioceras* cf. *oppeli* (GUÉRIN-FRANIATTE), *Arnioceras* cf. *ceratitoides* (QU.) (own data); *Arnioceras* cf. *oppeli* (GUÉRIN-FRANIATTE), *Arnioceras* cf. *falcarius* (QU.), *Arnioceras* cf. *robustum* (QU.), data from B. Hostettler (FPJ, 2005); ψ = *Microderoceras* sp., *Asteroceras* cf. *alamanicum* (GUÉRIN-FRANIATTE), data from B. Hostettler (FPJ, 2005); ω = ostracods (own data, det. E. Beher 2004); *Acroclythere oeresundensis*, *Bairdia*? *extracta*, *Bairdia molesta*, *Bythocypris postera*, *Isobythocypris tatei*, *Ledahia bispinosa*, *Ogmoconcha* aff. *amalthaei*, *Paracypris* sp., *Paracypris alemannica*

4.11.1 Gipf Bed

Names previously in use are given in Figs. 2 and 4.

Type locality Gipf clay pit (SW Frick; canton Aargau; coord.: 642.125/261.775; Rieber 1973).

Underlying strata Rietheim Member.

Overlying strata The Gipf Bed forms the basal layer of the Gross Wolf Member.

Occurrence The Gipf Bed is only developed within the area where the Rietheim Member is present (Fig. 3): Klettgau area, Zürcher Weinland, Tabular Jura, eastern Folded Jura and possibly also in the Mont Terri area. In the Hauenstein area, there is a significant reduction in thickness and facies interfingering with the Erlimoos Member is observed (see Jordan 1983; Wetzel and Reisdorf 2007).

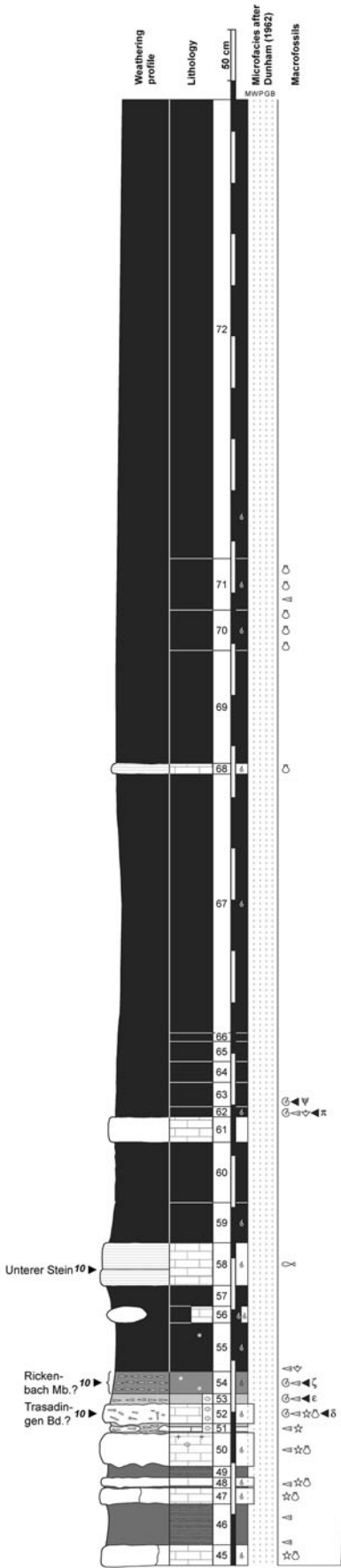
Thickness 0 to some 175 cm (see Jordan 1983; Richter 1987; Tröster 1987).

Chronostratigraphic age early Late Toarcian (Variabilis zone; Rieber 1973; Jordan 1983; cf. Knitter and Ohmert 1983; Knitter and Riegraf 1984; Richter 1987; Etzold et al. 1989; Kuhn and Etter 1994).

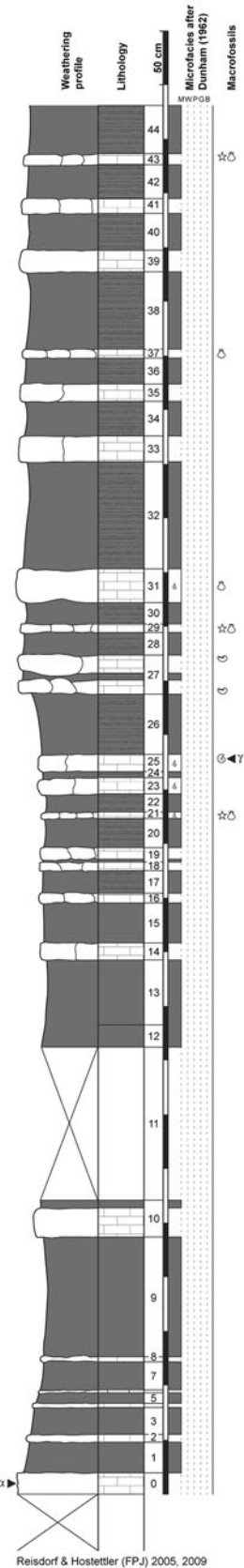
Description The facies of the Gipf Bed varies widely in the study area. This facies variation is mainly related to the thickness of the Gipf Bed. Essentially, the observed facies are condensed, yellowish to grey, glauconite-bearing, sometimes pyritic and sometimes bituminous marls, rich in fossils (especially belemnites; Jordan 1983; Nagra 1990; Kuhn and Etter 1994; cf. Fischer 1964). Concretionary limestone layers of up to about 20 cm thickness can be intercalated in the thickest intervals of these marls (Richter 1987; Tröster 1987; Kuhn and Etter 1994; cf. Fischer 1964). In addition, the Gipf Bed can contain limestone clasts that originate from the Rietheim Member or, in the

Section Les Salins (JU); coord.: 578.800 / 248.080

Pliensbachian	Toarcian		Stage
	Early	Early	Sub-stage 7
	Breitenmatt Mb.	Rietheim Mb.	Member 10
	"knollige Kalkbänke"	Posidonienschiefer	Member 16
Davoei	(S) (Ten.) ^β	Falçifer	Ammonite zone 3
	M.		(Bifrons)



?	Pliensbachian		Stage
?	(Sinemurian)	Early	Sub-stage 7
?	(Late)	Mont Terri Mb.	Member 10
Gryphiten-kalke	Obtustone	"knollige Kalkbänke" (= Obliqua-Schichten & Mitellias)	Member 16
	(bex)	Davoei	Ammonite zone 3
	(Raricostatum) (Jamesoni)		



Reisdorf & Hostettler (FPJ) 2005, 2009

◀ **Fig. 26** Detailed section of the Early Jurassic strata at Les Salins (SE Courtemaury/JU). α = compare Fig. 27; β = compare Richter (1987: 141), Pharissat et al. (1993) and Kuhn and Etter (1994); γ = *Aegoceras* cf. *maculatum* (Y. & B.); note the large minimal thickness solely for the sediments of the Davoei zone (at least 7.8 m); δ = *Becheiceras* sp., *Prodactylioceras davoei* (Sow.); ε = *Lytoceras fimbriatum* (Sow.), *Becheiceras* sp., *Androgynoceras capricornus* (SCHL.), *Oistoceras angulatum* (QU.), *Prodactylioceras davoei* (Sow.), *P. davoei enode* (QU.); ζ = *Lytoceras fimbriatum* (Sow.), *Amaltheus* cf. *stokesi* (Sow.), *Amaltheus bifurcus* (HOWARTH), see also Schmidt et al. (1924), Glauser (1936) and Vonderschmitt (1942); π = *Dactylioceras* sp., *Discina* sp.; ψ = *Dactylioceras* sp.

case of oolitic clasts, may even be derived from the Gipf Bed itself (Richter 1987 vs. Rieber 1973; Kuhn and Etter 1994). The bituminous facies is characterised by one bioturbated layer, where it is thinly developed, and even by several, if thicker (Riegraf et al. 1984: 61pp.; Richter 1987), which then resemble the youngest layers of the

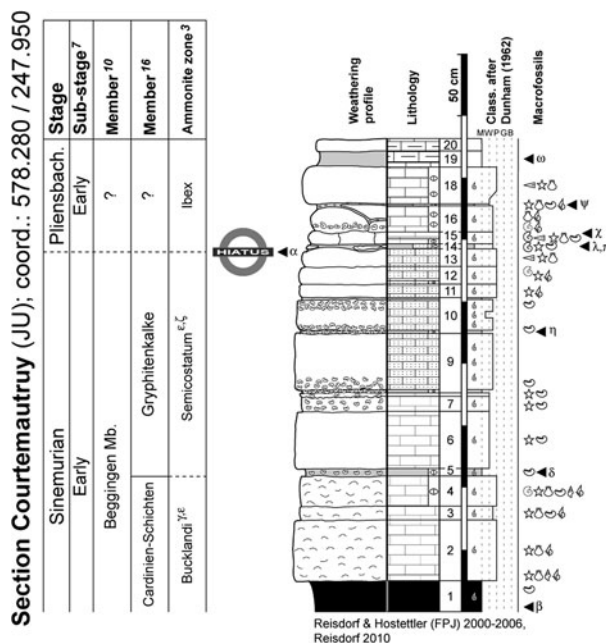


Fig. 27 Detailed section of the Early Jurassic strata at Courtemaury (JU). α = no indications for disturbances caused by postjurassic tectonic processes or landslides could be detected in this sedimentary succession (section established by Reisdorf 2005); β = compare Buxtorf (1910); γ = loosely collected *Angulaticeras angulatooides* (QU.); δ = ostracods (own data, det. E. Beher 2004): *Bairdia fortis*, *Isobythocypris tatei*, *Ledahia* sp., *Ogmoconcha* sp.; ε = loosely collected *Arietites* sp., *Arietites* s.l.; ζ = loosely collected *Paracorniceras* s.l.; η ostracods (own data, det. E. Beher 2004): *Bairdia molesta*, *Cardobairdia liasica*, *Ledahia* sp., *Pseudohealdia*? sp.; λ = *Beaniceras* sp.; π = ostracods (own data, det. E. Beher 2004): *Bairdia fortis*; χ = *Coroniceras* sp.; ψ = ostracods (own data, det. E. Beher 2004): *Bairdia molesta*, *Cardobairdia liasica*, *Isobythocypris tatei*; ω = ostracods (own data, det. E. Beher 2004): *Bairdia fortis*, *Bairdia molesta*, *Bairdia michelseni*?, *Bairdiacypris anisica brevis*, *Bythocypris postera*, *Cardobairdia* sp. 3, *Cardobairdia liasica*, *Isobythocypris tatei*, *Ledahia* sp., *Ogmoconcha* sp., *Ostracode* E, *Paracypris*? *redcarensis* (Beher 2004)

Rietheim Member (e.g., *Fucoidengrenzbank* of Kuhn and Etter 1994; see Richter 1987). In the thinnest occurrences (40 cm and less) that are occur in the western Tabular Jura and the eastern Folded Jura, the marly facies of the Gipf Bed can merge laterally with a ferruginous or iron oolitic limestone which is occasionally overgrown by stromatolites (Fig. 10, Rieber 1973; Jordan 1983; Kuhn and Etter 1994; cf. Knitter and Riegraf 1984; Riegraf 1986).

4.11.2 Erlimoos Bed

Names previously in use are given in Figs. 2 and 4.

Type locality Erlimoos clay pit (NE Olten; canton Solothurn; coord.: 633.400/247.050; Fig. 13).

Underlying strata Rietheim Member (including Unterer Stein) or Breitenmatt Member (including Müsenegg Bed).

Overlying strata The Erlimoos Bed forms the base of the Gross Wolf Member.

Occurrence Hauenstein area to Bernese Jura and adjacent areas to the south in the Molasse Basin (see Jordan 1983; Nagra 1992; Figs. 17, 20). In the Hauenstein area facies interfingering occurs between the Erlimoos Bed and the Gipf Bed (see Kuhn and Etter 1994; Maisch and Reisdorf 2006a, b).

Thickness 0–40 cm (e.g., Figs. 19, 20).

Chronostratigraphic age Early Late Toarcian (Variabilis zone; Imhof in Jordan 1983; Kuhn and Etter 1994; Reisdorf 2001).

Description Strongly condensed, phosphoritic, glauconitic marls rich in fossils or marly limestone of small thickness (Figs. 12, 13, 17, 18, 19, 20, 21; see Erni in Mühlberg 1915; Jordan 1983; Kuhn and Etter 1994). In addition, clasts and even boulders occur, as well as macrofossils that display evidence of reworking, such as phosphatised ammonites (Fig. 19; see Erni in Mühlberg 1915; Imhof in Jordan 1983; cf. Groschopf et al. 1977: 115p.). In the Hauenstein area, the Erlimoos Bed also contains disarticulated and often fragmented reptilian skeletal elements (= exhumed and reworked vertebrate fragments of the Rietheim Member?; Figs. 13, 17; see Meyer and Furrer 1995; Reisdorf et al. *subm.*).

The biostratigraphically orderless appearance of index fossils (ammonites, ostracods, foraminifers) indicates substantial reworking and bioturbation during the formation of the Erlimoos Bed (see Hess 1962; Jordan 1983; Richter 1987; Wetzel and Reisdorf 2007). In some areas, the erosive base cuts down to the Ibex zone, possibly even down to the Jamesoni zone of the Breitenmatt Member (Figs. 3, 17; see Erni in Mühlberg 1915; Jordan 1983; Wetzel et al. 1993).

The Erlimoos Bed and certain phosphoritic layers of the Pliensbachian (see Breitenmatt Member and Müsenegg Bed) may have a quite similar appearance. In contrast to the Breitenmatt Member (including the Müsenegg Bed), the Erlimoos Bed is, however, often overgrown by sponges in phosphoritic preservation and pyritised stromatolites: Even larger surfaces may be encrusted here without significant gaps (Figs. 13, 17, 18, 20; see Jordan 1983; cf. Ohmert 1976; Etzold 1980). This stratigraphic level is detectable even in drill cores because of its peculiar facies. An additional feature of the Erlimoos Bed is the absence of gryphaeid oysters, unlike the Breitenmatt Member.

4.11.3 Eriwis Bed

Names previously in use are given in Figs. 2 and 4.

Synonym Erimis Bed (Jordan et al. 2008).

Type locality Eriwis (canton Aargau; coord.: 652.000/256.250; Etter 1990; Kuhn and Etter 1994).

Underlying strata The Eriwis Bed forms the topmost layer of the Gross Wolf Member.

Overlying strata Opalinus-Ton (e.g., Etter 1990; Wetzel and Allia 2003; Franz and Nitsch 2009).

Occurrence Eastern Folded Jura and adjacent areas to the south in the Molasse basin of the Swiss Midland (Fig. 23; see Buxtorf 1907; Jordan 1983; Nagra 1992; Pfirter 1997).

Thickness ?0 to ca. 30 cm (Figs. 19, 23; see Fischer and Luterbacher 1963; Jordan 1983).

Chronostratigraphic age Late Toarcian (Levesquei zone; Aalensis subzone; Etter 1990; Reisdorf et al. [subm.](#)).

Description Only a few centimetre thick, condensed horizon of the Aalensis subzone (see Etter 1990; Wetzel and Reisdorf 2007; Reisdorf et al. [subm.](#); cf. Etzold 1980). Occasionally brownish, sometimes reddish, dark grey marl layer which may pass laterally into a marly limestone (Figs. 11, 12, 13, 15, 16, 17, 18, 23). This phosphoritic condensed horizon is characterised by its abundance of ammonites (especially the genera *Cotteswoldia* and *Pleydellia*, among others also *C. aalensis* ZIETEN 1832) and belemnites (Jordan 1983; Etter 1990; Nagra 1992; cf. Etzold et al. 1989). Based on these characteristics, the Eriwis Bed is clearly and visibly separated from the overlying Opalinus-Ton (see Jordan 1983; Etter 1990; Reisdorf 2001). The latter is characterised by dark grey to black, partially silty to sandy terrigenous mudstone and marl with mica (Etter 1990; Reisdorf 2001; Wetzel and Allia 2003). In the Schafisheim well the lithostratigraphic boundary between the Gross Wolf Member and the

Opalinus-Ton is set below a 15 cm thick, reworked horizon that contains iron ooids and Mid-Jurassic foraminifera. This mudstone horizon is noteworthy because it also contains corroded ammonites of the Late Toarcian (*Cotteswoldia aalensis* ZIETEN 1832; Tröster 1987; Nagra 1992).

5 Concluding remarks

The total thickness of the Early Jurassic deposits in northern Switzerland is around 25–50 m and thus is significantly thinner than in the adjacent areas of Germany and France (Fig. 6). Lithostratigraphic units of the Early Jurassic that are conformable with the southwest German or eastern French nomenclature therefore only occur in reasonable thickness in the northernmost Tabular Jura (Hofmann 1981; Debrand-Passard 1984; Hofmann et al. 2000, 2002; Bloos et al. 2005). The often small thickness of the majority of the northern Swiss Early Jurassic strata, however, only qualify the complete stratigraphic interval as a mappable unit (= Staffelegg Formation).

In the Klettgau area, the Tabular Jura and the eastern Folded Jura, up to 90% of the total thickness is represented by Sinemurian deposits. By contrast, Pliensbachian and Toarcian deposits account for up to 70% of the total thickness of the Early Jurassic in the western Folded Jura (Mont Terri area). The Early Jurassic strata of the Klettgau area and the Tabular Jura show strong analogies to the facies in southwestern Germany. Significant changes in facies occur towards the south, accompanied by a gradual decrease in thickness (Figs. 3, 6). In addition, stratigraphic gaps occur on a local to regional scale throughout northern Switzerland (Fig. 3). Such hiatus may span a subzone to a stage in time. Consequently it is not always possible to fully reconcile the Early Jurassic sediments, especially of the Folded Jura, with the stratigraphic nomenclature of southwestern Germany (cf. Bloos et al. 2005; Schmid et al. 2008). Especially, in the southernmost and westernmost Folded Jura and in the Molasse Basin abrupt facies changes occur. The impression of strongly differentiated facies patterns is intensified by the folding of the Jura Mountains that led to a shortening of original distances (cf. Laubscher 1965, 2008).

In the westernmost part of the study area (Mont Terri area) the facies and thickness of the Early Jurassic strata show stronger affinities to those found in eastern France than in southwestern Germany (cf. Vonderschmitt 1942; Théobald 1967; Debrand-Passard 1984; Pharissat et al. 1993). The most striking is that thickness of Sinemurian to Toarcian strata is remarkably thicker than to the East, in particular the Early Toarcian bituminous deposits (Fig. 26; Rickenbach 1947; Bitterli 1960; Contini and Lamaud

1978). The strata of the Late Sinemurian to Early Pliensbachian in the Mont Terri area distinctly differ from the sediments of the same age to the east (Fig. 3). The lithology in the Mont Terri area requires a new member (= Mont Terri Member) that differs from the previous stratigraphic nomenclature of northern Switzerland. Because of lacking outcrops in an area east of the Mont Terri it is impossible to precisely define the lateral extent of the Mont Terri Member. The maximum age of this member in the eastern Mont Terri area is Obtusum zone, based solely on lithostratigraphic correlation. The dating in the western Mont Terri area is, however, based on an ammonite of the Ibex zone that was found just above strata of the Semicostatum zone (Fig. 27). Consequently, the base of the Mont Terri Member is heterochronous. Following this interpretation, the erosion during the Early Pliensbachian that cut down into the strata of Early Sinemurian age is likely to have occurred in some parts of the Mont Terri area (Fig. 3).

The Early Jurassic strata in northern Switzerland can be subdivided into three facies domains: (1) Klettgau area, Tabular Jura and immediately adjacent areas of the Molasse basin (mainly corresponding to the facies in southwestern Germany, i.e. Swabian Basin), (2) eastern Folded Jura and immediately adjacent area of the Molasse basin (with a discrete “northwestern Swiss facies” of the Swabian Basin) and, (3) Mont Terri area (Folded Jura; facies that shows a strong affinity to the eastern Paris Basin in its stratigraphic architecture).

The main characteristics of the stratigraphic architecture of these three facies domains are represented by 11 members and 9 beds in the Staffelegg Formation. The members that have been defined for the Folded Jura differ significantly from the classification schemes previously in use for the Early Jurassic of northern Switzerland. The beds defined within the Staffelegg Formation serve as connecting elements between the traditional and new stratigraphic nomenclature. They represent supracoregional marker beds with the exception of the Müsenegg Bed and the Eriwis Bed. Some of the beds are developed as thin strata in the sense of allostratigraphy (Hallau Bed, Müsenegg Bed, Gipf Bed; cf. Lutz et al. 2005). Namely the Hallau Bed (Planorbis to Liasicus zone), Schleithem Bed (Angulata zone), Gächlingen Bed (Bucklandi zone), Trasadingen Bed (Davoei zone) and the Unterer Stein (Falcifer zone) have lithostratigraphic equivalents in southwestern Germany (Fig. 2).

Only one of these beds, Unterer Stein, can be traced with some confidence to the Mont Terri area and from there to France (cf. Riegraf et al. 1984: 14p.; Pharissat et al. 1993; Kuhn and Etter 1994). The questionable Trasadingen Bed in the Mont Terri area (Fig. 26) could be correlatable to the so-called Banc à Davoei in France (cf. Debrand-Passard 1984: 136). The Gipf Bed and Erlimoos Bed, in contrast,

correlate with erosion horizons of the Variabilis zone in southwestern Germany and eastern France (cf. Rieber 1973; Debrand-Passard 1984; Knitter and Ohmert 1983). The Gipf Bed and Erlimoos Bed occur in characteristic development south of the Rhine River, in particular when they are thin. The same is true for the Müsenegg Bed (Margaritatus to Spinatum zone) and the Eriwis Bed (Aalensis subzone) that only occur in the Folded Jura and in the Molasse Basin to the south.

The Staffelegg Formation is introduced for Early Jurassic sediments in northern Switzerland between the Doubs River and the Mount Weissenstein in the West and the Randen Hills north of the city of Schaffhausen in the East. To the South and East, in boreholes in the Molasse Basin, a transition to a facies more proximal to the Vindelician land mass was observed (cf. Büchi et al. 1965; Trümpy 1980; Stoll-Steffan 1987). Early Jurassic strata underneath the frontal part of Imbricated Molasse (e.g., well Entlebuch 1; Vollmayr and Wendt 1987) and those of the Lake Constance area cannot be consistently subdivided into the members and beds of the Staffelegg Formation (cf. Stoll-Steffan 1987). For these occurrences additional lithostratigraphic units are required to account for the coastal facies of the Swabian Basin. An extension of the Staffelegg Formation to the area of Lake Bienné (well Hermrigen, coord.: 584.600/214.880) and to areas further to the west is not advisable, however, since the Early Jurassic occurrences in these areas are developed in the facies of the Rhodanian Basin (cf. Fischer and Luterbacher 1963; Büchi et al. 1965; Jordan et al. 2008 and references therein).

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Chapter II

Sea-Level

Palaeobiodiversity and Palaeoenvironments

Float, explode or sink: postmortem fate of lung-breathing marine vertebrates

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Abstract What happens after the death of a marine tetrapod in seawater? Palaeontologists and neontologists have claimed that large lung-breathing marine tetrapods such as ichthyosaurs had a lower density than seawater, implying that their carcasses floated at the surface after death and sank subsequently after leakage of putrefaction gases (or “carcass explosions”). Such explosions would thus account for the skeletal disarticulation observed frequently in the fossil record. We examined the taphonomy and sedimentary environment of numerous ichthyosaur skeletons and compared them to living marine tetrapods, principally cetaceans, and measured abdominal pressures in human carcasses. Our data and a review of the literature demonstrate that carcasses sink and do not explode (and spread skeletal elements). We argue that the normally

slightly negatively buoyant carcasses of ichthyosaurs would have sunk to the sea floor and risen to the surface only when they remained in shallow water above a certain temperature and at a low scavenging rate. Once surfaced, prolonged floating may have occurred and a carcass have decomposed gradually. Our conclusions are of significance to the understanding of the inclusion of carcasses of lung-breathing vertebrates in marine nutrient recycling. The postmortem fate has essential implications for the interpretation of vertebrate fossil preservation (the existence of complete, disarticulated fossil skeletons is not explained by previous hypotheses), palaeobathymetry, the physiology of modern marine lung-breathing tetrapods and their conservation, and the recovery of human bodies from seawater.

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Introduction

Large vertebrate fossils such as ichthyosaurs are spectacular documents of earth history, but uniformitarian studies of the fate of large vertebrate carcasses in shallow marine environments before fossilization are rare (Britton and Morton 1994; Dahlgren et al. 2006; Glover et al. 2005; Liebig et al. 2007; Schäfer 1972; Smith 2007a). Recent studies have mainly dealt with decomposition of vertebrate carcasses in the deep sea (e.g., Glover et al. 2008; Kemp et al. 2006; King et al. 2006; Smith and Baco 2003). Because of the usual lack of food at the deep-sea floor, the scavenging rate on carcasses can be much higher than in shallow marine habitats (Bozzano and Sardà 2002; Janßen et al. 2000; Kemp et al. 2006). Consequently, direct comparisons between deep and shallow marine habitats are of only limited value (e.g., Fujiwara et al. 2007; Martill et al. 1995; Smith 2007a), since physical, chemical, and microbial decomposition are significantly more important than scavenging in the shallow-water (Anderson and Hobischak 2004; Kahana et al. 1999; Mosebach 1952; Petrik et al. 2004; Smith and Baco 2003).

We thus examined peri- and postmortem processes concerning carcasses of lung-breathing vertebrates in a shallow marine regime by applying palaeontological, sedimentological, forensic, anthropological, archaeological, veterinary, marine biological, and trophological methods. This integrative approach enabled us to falsify several previously applied hypotheses to explain taphonomic phenomena. It is our aim to portray the processes involved in the stratinomy of lung-breathing vertebrates, to falsify some old hypotheses, and to discuss possible applications.

Ichthyosaurs represent a diverse group of extinct marine reptiles which were almost cosmopolitan during most of the Mesozoic [245–90 million years ago (Ma); Gradstein et al. 2004; McGowan and Motani 2003]. Although these fossil lung-breathing tetrapods exhibit a whole set of morphological characters which evolved convergently to the Odontoceti (cetaceans), it has been assumed that ichthyosaur bodies had a lower density than seawater (e.g., McGowan 1992; McGowan and Motani 2003; Taylor 1987, 2001). The prevailing interpretation implies that ichthyosaurs drifted after death for a while at the sea surface and the preservation quality decreased with the floating duration (e.g., Fröbisch et al. 2006; Long et al. 2006; Martill 1986, 1993). The carcasses sank finally to the sea-floor only after leakage of the putrefaction gas, often by bursting (e.g., Cruickshank and Fordyce 2002; Kuhn-Schnyder 1974; Long et al. 2006; Martill 1993; commonly called “carcass explosion”).

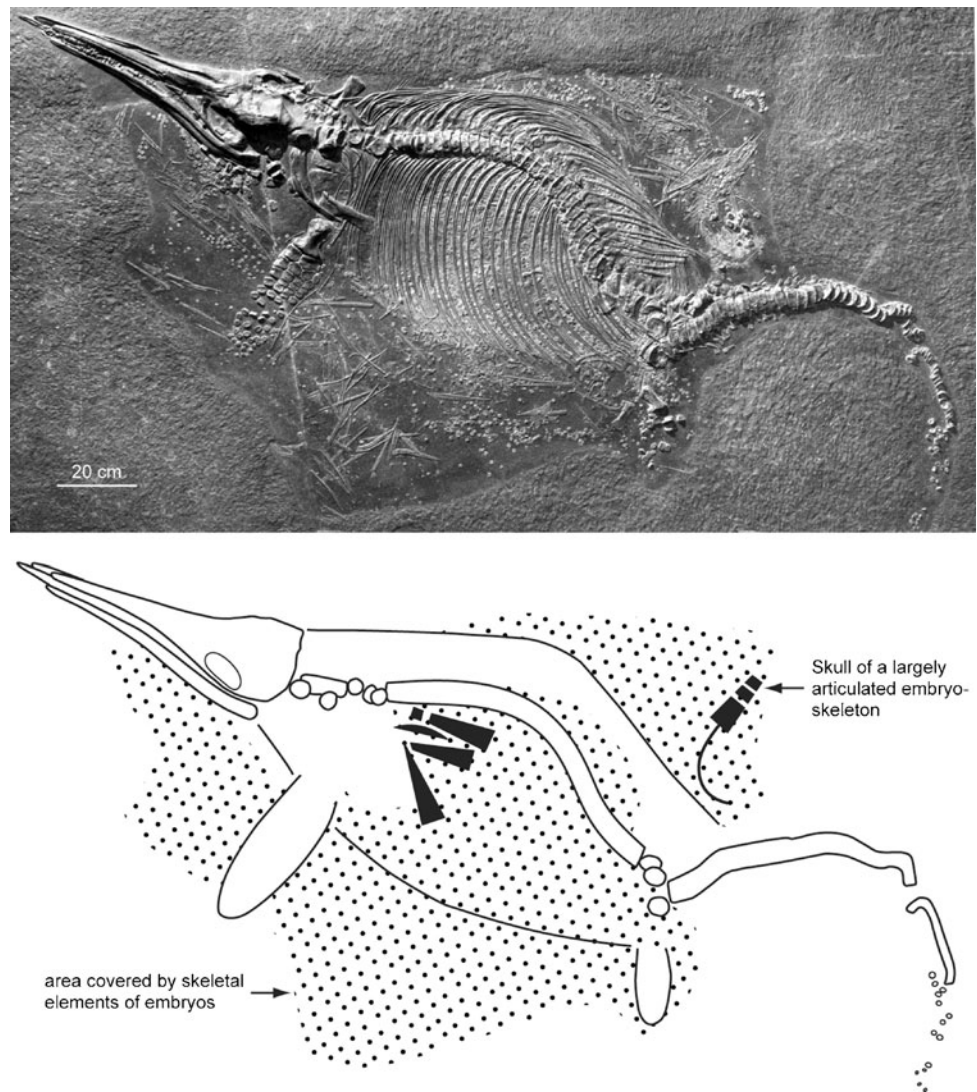
Ichthyosaurs were probably able to dive to depths exceeding 500 m (Dollo 1907; Humphries and Ruxton 2002; McGowan and Motani 2003). This inference can be drawn from the absence of ossified tracheas in fossil ichthyosaurs, which can otherwise be preserved in great detail in marine crocodiles of the same age and localities as the ichthyosaur finds (e.g., Westphal 1962). A more or less ossified trachea limits diving depth (Mason and Macdonald 1986; Tarasoff and Kooyman 1973), and the tracheas of Recent, deep-diving lung-breathers are cartilaginous (Kooyman 1989). Such cartilaginous tracheas are usually not preserved in the fossil record.

Exploding the myth: can carcasses explode?

“Carcass explosion” was first discussed among palaeontologists and geologists 32 years ago (Keller 1976), when studying the Early Jurassic Posidonienschiefer Formation (Bloos et al. 2005; ca. 183–181 Ma) of Germany. These black shales were deposited at depths between 50–150 m (Röhl et al. 2001) and contain exceptionally well-preserved remains of ichthyosaurs and other marine tetrapods (Hauff 1921; Hofmann 1958; Martill 1993). The excellent fossil preservation within finely laminated, unbioturbated black shales was explained with the widely accepted classic “stagnant basin model” (Keller 1976; Pompeckj 1901). The ichthyosaur skeletons are usually complete but disarticulated to varying degrees (Hauff 1921; Hofmann 1958). Therefore, “carcass explosion” appeared to be a reasonable explanation. It was assumed that carcasses which lie on the sea-floor might have exploded or internal organs and bones erupted, and that in so doing, bones as well as fetuses were ejected and ribs were fractured (Fig. 1; e.g., Böttcher 1989; Hofmann 1958; Keller 1976; Martill 1993). In spite of the lack of (direct) evidence for these processes, these ideas have never been questioned.

These classic models rely on the observation that beached Cetacean carcasses can get inflated impressively by putrefaction gases within hours (=bloated stage; Malakoff 2001; Schäfer 1972; Smith and Baco 2003; Stede et al. 1996; Tønnessen and Johnsen 1982). This process is mainly initiated by the activity of intestinal bacteria (=intrinsic flora; Daldrup and Huckenbeck 1984; Fiedler and Graw 2003; Mallach and Schmidt 1980; Robinson et al. 1953; Stevens and Hume 1998). Postmortem bacterial activity is highly variable because it depends on numerous factors such as the type of bacteria involved, the cause of death, injuries, and composition and amount of ingested food, as well as environmental conditions (Bajanowski et al. 1998; Daldrup and Huckenbeck 1984; Keil et al. 1980; Mallach and Schmidt 1980; Pedal et al. 1987; Pierucci and Gherson 1968; Rodriguez 1997; Sakata et al. 1980). Putrefaction rates decelerate with decreasing (water) temperature (Bonhotal et al. 2006; Dickson et al. 2011; Haberda 1895; Padosch et al.

Fig. 1 Ichthyosaur skeleton with approximately 10 embryos, Holzmaden (Germany), Posidonienschiefer Formation (*Stenopterygius*, specimen SMNS 50007; drawing modified after Böttcher 1990; image by courtesy of Staatliches Museum für Naturkunde Stuttgart). In contrast to the skeleton of the mother, most of the embryonal skeletons are largely disarticulated. Many embryonal bones are scattered far beyond the body limits of the mother. Böttcher (1990) explained this arrangement by a displacement of already disarticulated embryos during the expulsion of putrefaction gases through the ruptured body wall of the mother. Osborn (1905) explained such phenomena by currents by currents



2005; Petrik et al. 2004; Robinson et al. 1953). Decay by intestinal bacteria (e.g., *Clostridia*, *Escherichia*) all but halts below 4°C, while enzymes (=autolysis) remain active until –5°C (Jauniaux et al. 1998; Keil et al. 1980; Lochner et al. 1980; Robinson et al. 1953; Sharp and Marsh 1953; Vass et al. 2002; compare Rollo et al. 2007). In aquatic environments, putrefaction and autolysis progresses most rapidly at low hydrostatic pressures within an intact, large, cylindrical and well-insulated carcass (e.g., a whale; Hood et al. 2003; Innes 1986; McLellan et al. 1995; Robinson et al. 1953; Worthy and Edwards 1990), independent of oxygen availability. When an inflated carcass experiences mechanical stress such as inappropriate transport or dissection, body liquids and internal organs may be ejected from the carcass (Fig. 2; Anonymous 2004; Stede 1997; Tigress Productions 2008; Tønnessen and Johnsen 1982). There is no evidence for skeletal elements being included in such “eruptions”.

During the Toarcian, the conditions in the European epeiric sea were favourable for putrefaction and autolytical processes,

because the sea surface temperature has been estimated to have varied between 25 and 30°C (Röhl et al. 2001).

In spite of the adaptations to the marine habitat, it is still probable that sometime after death seawater containing anaerobic or aerobic bacteria intruded both digestive and respiratory tracts of ichthyosaurs because of the hydrostatic pressure (=exogenous bacteria; e.g., Eisele 1969; Hänggi and Reisdorf 2007; Kakizaki et al. 2008; Siebert et al. 2001; Sims et al. 1983). Onset of putrefaction processes due to exogenous bacteria is thus conceivable (as in human carcasses; Davis 1986; Dickson et al. 2011; Lunetta et al. 2002; Mallach and Schmidt 1980; Padosch et al. 2005; Tomita 1975, 1976). The putrefaction gases produced by the intrinsic bacteria but probably also by exogenous bacteria comprise CO₂, H₂, N₂, to a lesser amount CH₄, H₂S, and even O₂ (Keil et al. 1980; Mallach and Schmidt 1980; see also Ettwig et al. 2010). To obtain data for the pressure that builds up in carcasses in different stages of bloating, intra-abdominal pressures were measured in 100 human corpses at the Institut

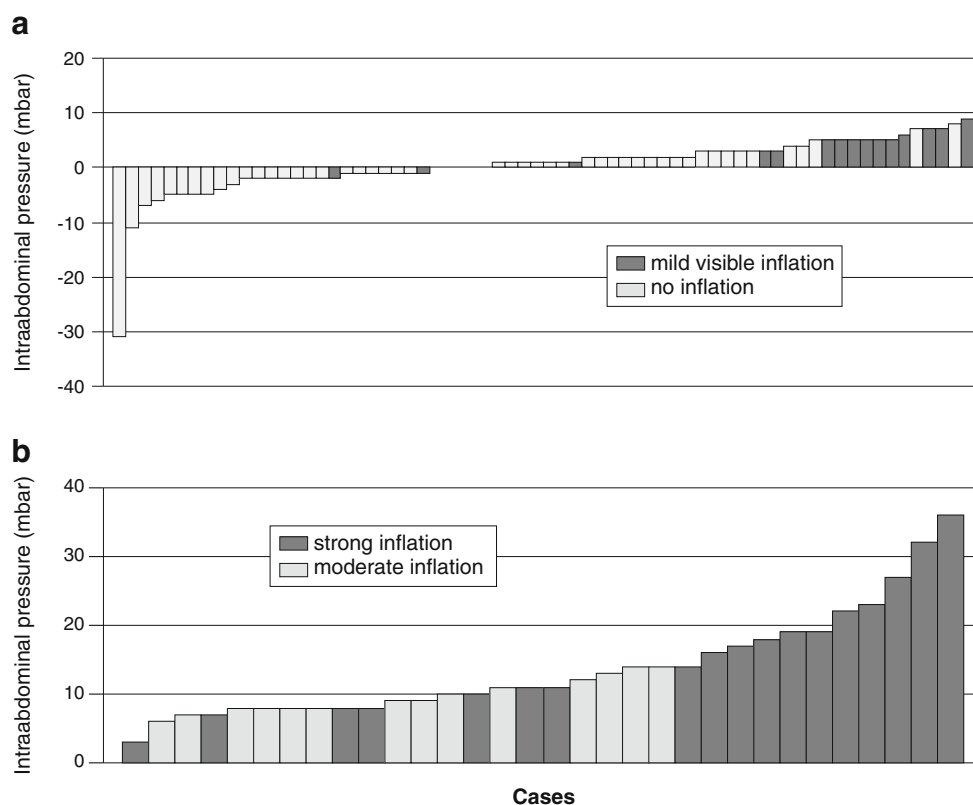


Fig. 2 Improper sectioning of a stranded whale carcass bloated by putrefaction gases at the beach of Nymindegab/ Denmark; body liquids and parts of the intestinal tract erupt violently from the body cavity (Krarup 1990; image by courtesy of TV/Midt-Vest)

für Forensische Medizin Frankfurt am Main in 2004 (Bux et al. 2004). The manometer (C9557 Pressure Meter; Comark, Hertfordshire, UK) was introduced into the abdominal cavity

in the vicinity of the umbilicus by means of an anasarca trocar. The intraabdominal pressures did not exceed 0.035 bar (Fig. 3). This agrees with the pressures which were measured

Fig. 3 Relationship between effective intra-abdominal pressures and bloated stages in 100 human corpses (measured between January 1 and August 30, 2004). **a** Intraabdominal pressures at no (light grey bars) or mild (dark grey bars) visible inflation. Intra-abdominal pressures lower than atmospheric pressures are due to postmortem cooling of the corpses. **b** Intraabdominal pressures at moderate (light grey bars) or strong (dark grey bars) visible inflation. The range of intraabdominal pressures due to bloating by putrefaction gas is comparable to the pressures used in laparoscopic surgery (Abu-Rafea et al. 2006)



by Fallani (1961) in human dead bodies. In goat carcasses, however, pressures up to 0.079 bar have been recorded (Li et al. 2003). These pressure values correspond to submersion depth in water of 0.35 and 0.79 m. In the case of ichthyosaur carcasses that sank to the bottom of the Toarcian epeiric sea in Europe, potential hydrostatic pressures corresponding to a water depth of 50–150 m would reach 5–15 bar (Boyle's law; e.g., Haglund and Sorg 2002; Toklu et al. 2006; Tomita 1975). It is highly unlikely that intraabdominal pressures in the most common European ichthyosaur *Stenopterygius quadriscissus* (which usually attained 1.5–2.9 m in length; e.g., von Huene 1922; McGowan and Motani 2003) exceeded these values, and therefore, “carcass explosion” was impossible in greater water depths, close to or at the water surface. This appears even more unlikely because ichthyosaur fetuses are commonly found directly adjacent to the carcass of their mother in calculated water depths of 50–150 m (Fig. 1; Böttcher 1990; Hofmann 1958; Röhl et al. 2001), where such explosions are physically impossible.

Subsequently, we present two models explaining disarticulation of ichthyosaur skeletons of the Posidonienschiefer Formation. The burial depth of the carcass (0–100% covered by sediment) plays an important role. This is especially true since the palaeoenvironment of the Posidonienschiefer Formation was neither entirely nor continuously anoxic (e.g., Kauffman 1981; Röhl et al. 2001; Röhl and Schmid-Röhl 2005).

Effects of sediment compaction and currents

Even in an oxygen-deficient environment, preservation potential of carcasses of marine tetrapods depends on burial depth (Hofmann 1958; Martill 1993). Organic-rich mudrocks such as the Early Jurassic Posidonienschiefer Formation exhibit a high initial porosity. During some time intervals, the topmost decimetres of the sediment were probably nearly fluid (“soupy substrate”; Hofmann 1958; Martill 1993; Röhl et al. 2001). The physical properties of such “soupy substrates” enabled ichthyosaur carcasses to sink into the sediment partially or entirely [e.g., Hofmann 1958; Martill 1993; Schimmelfennig et al. 1994; Smith and Wuttke (2012, this issue), however, critically evaluate this taphonomic scenario of embedding of ichthyosaur carcasses]. Afterwards, the sediment was compacted by over 90% due to burial, causing intense brittle and “plastic” deformation of the skeleton parts (Einsele and Mosebach 1955; Hofmann 1958; Martill 1993) unless embedded in early diagenetic concretions (Keller 1992; Wetzel and Reisdorf 2007). The most intense deformation during compaction occurred in the thorax, causing the ribs to depart from their original arrangement and, as documented in some ichthyosaur fossils, from phosphatized or pyritized soft part remains (e.g., the stomach) near the abdominal and cloacal regions (Hofmann 1958; Keller

1976). These phenomena resemble injuries of an originally intact body characteristic of “crush/traumatic asphyxia” (e.g., Byard et al. 2006; Machel 1996), and this type of preservation contradicts explosion.

Organic-rich, muddy sediments like the Posidonienschiefer Formation are stated to accumulate mainly under prevailing tranquil conditions (e.g., Seilacher 1982). Evidence for weak to moderate currents, however, can be encountered in nearly all levels of the Posidonienschiefer Formation, indicating fluctuations in the depositional environment (Kauffman 1981; Röhl and Schmid-Röhl 2005; Schieber et al. 2007). Indeed, recent experiments show that such mud can be deposited from currents moving at 0.1–0.26 m/s (Schieber et al. 2007). The erosion of such cohesive sediments requires high current velocities, depending on the degree of consolidation because of the electrostatic forces between particles (Sundborg 1956). Bacteria–particle interactions at the sediment surface might also increase the resistance against erosion (Black et al. 2003; Röhl et al. 2001; Widdel 1988). The low net sedimentation rate of the Posidonienschiefer Formation of 4 mm/1,000 years (calculated for compacted sediments; Röhl et al. 2001) and the high compressibility of such sediments might have favored dewatering of an initially “soupy substrate” (e.g., Bernhard et al. 2003; Wetzel 1990). Flume-experiments with human and animal bones (density of dry and wet bones is usually below 2.65; Blob 1997; de Ricqlès and de Buffrénil 2001; Lam et al. 2003) revealed that bones of the thorax and the appendages begin to move at current velocities as low as 0.2–0.4 m/s (e.g., Blob 1997; Boaz and Behrensmeyer 1976; Coard 1999; Fernández-Jalvo and Andrews 2003). Such currents have been postulated for the shallow marine Early Toarcian epeiric sea (e.g., Hofmann 1958; Kauffman 1981; Martill 1993; Röhl and Schmid-Röhl 2005). The histology of ichthyosaur bones displays some convergences to Recent cetacean bones, which possess a lower density than land tetrapods (de Buffrénil et al. 1986; de Ricqlès and de Buffrénil 2001; Maas 2002). A further density decrease might have been caused by decay, microbial activity, and bone diagenesis (Arnaud et al. 1980; Fujiwara et al. 2007; Glover et al. 2005; Kiel 2008; Meyer 1991; Smith and Baco 2003). Thus, there was a real potential for transport of ichthyosaur bones by water currents.

All these factors make it highly probable that currents moved bones on the seafloor without eroding mud. This deduction is supported by the fact that 90% of all ichthyosaur specimens are disarticulated (Hauff 1921). The arrangement of ichthyosaur skeletal remains documents that the carcass was not or incompletely embedded in sediment for a considerable time (physical properties of the topmost decimetres of the seabottom prevented carcasses from being embedded entirely). Under these conditions, soft-tissues initially decomposed, causing the loss of connectivity of the skeletal elements, and the carcass eventually collapsed gravitationally (Hofmann

1958; Martill 1993; Reisdorf and Wuttke 2012, this issue). Thoracic elements were most strongly affected by currents because they were usually exposed furthest above the ground and experienced highest current velocities. It is also conceivable that larger Metazoan scavengers played an additional role in the disarticulation and transport of skeletal elements (e.g., Kauffman 1981; Martill 1993; von Huene 1922), but the processes discussed above are of greater importance in a predominantly oxygen-deficient environment.

Sink or float?

The density of the ichthyosaur body and other aquatic lung-breathing tetrapods plays a crucial role in the potential to sink or float. Today, no Recent reptiles are known which can be considered as closely related to ichthyosaurs, especially with respect to anatomical and physiological characteristics. Therefore, Recent (facultatively) aquatic reptiles are only of limited use for such comparisons (e.g., Wade 1984). By contrast, Recent cetaceans (e.g., de Ricqlès and de Buffrénil 2001; Ridgway 2002; Sekiguchi and Kohshima 2003; Staunton 2005; Taylor 2000; Williams et al. 2000) may serve as a morphological and ecological model to reconstruct the postmortem fate of ichthyosaurs. With the exception of the species *Eubalaena glacialis* and *Physeter macrocephalus*, cetaceans have a density slightly higher than that of seawater (e.g., Butterworth 2005; Schäfer 1972; Shevill et al. 1967; Smith 2007a, b; Tønnessen and Johnsen 1982). *E. glacialis* and *P. macrocephalus* are relatively slow-swimming whales and the only species which usually does not sink after having been shot by whalers (Braham and Rice 1984; Gosho et al. 1984; Nowacek et al. 2001). [Jurassic Ichthyosaurs are usually considered to have been the fastest sustained swimmers of the Mesozoic seas (e.g., Lingham-Soliar and Wesley-Smith 2008) and thus seem also likely to have been negatively buoyant.] The low density of the bodies of these species, the so-called “right whales”, is caused by an extraordinarily high content of oil and fat (e.g., Glover et al. 2008; Gosho et al. 1984; Kemp et al. 2006; Slijper 1962). Other “right whales” (e.g. *Balaenoptera musculus*) may float after death only when caught by “Electrical Whaling”; paralyzed thoracic musculature apparently accounts for this phenomenon (Øen 1983).

Odontoceti might also become positively buoyant when the lungs are almost completely or entirely filled by air (e.g., Ridgway et al. 1969; Slijper 1962). Among living and etiologically unconditioned cetaceans, the lung volume never gets used exhaustively (Wartzok 2002). The respiration physiology of mammals, however, is significantly different from that of Recent reptiles; most of the latter exhale actively and inhale passively (Carrier and Farmer 2000; Perry 1983).

This line of reasoning suggests that even if inhalation in ichthyosaurs was passive as in Recent reptiles, they would still have been negatively buoyant (e.g., Hogler 1992; Wade 1984) and sunk immediately after death, unless the lungs were filled with air to an abnormal degree (e.g., pulmonary emphysema; Siebert et al. 2001; Slijper 1962; Ridgway et al. 1969; Fig. 4).

Incipient decomposition at the seafloor causes a reduction in carcass density. How far gaseous putrefaction products develop in the carcass, and whether they are dissolved or bound within the soft-tissues and body liquids, depends mainly on the local hydrostatic pressure and temperature (Allison et al. 1991; Dickson et al. 2011; Hofmann 1958; Lucas et al. 2002; McLellan et al. 1995; Smith and Baco 2003; Tomita 1975, 1976; Wasmund 1935; Zangerl and Richardson 1963). All main components of the putrefaction gas (N_2 , H_2 , O_2 ; possibly also CH_4) except for the CO_2 share a low solubility at temperatures below 4°C and moderate pressures ($O_2 > N_2 > CH_4 > H_2$; Ashcroft 2002: 59; Mallach and Schmidt 1980; Ramsey 1962; Shafer and Zare 1991; Weiss and Price 1989) and tend to increase buoyancy by forming bubbles (Dumser and Türkay 2008; Mueller 1953; Tomita 1975). It depends on the integrity of the skin and the digestive tract whether these gases can accumulate inside the carcass (beneath the skin and in the body cavities; Anderson and Hobischak 2004; Dumser and Türkay 2008; Haglund 1993; Schäfer 1972; Smith and Baco 2003; Thali et al. 2003).

In shallow water and at temperatures above 4°C, it is very likely that putrefaction gases would cause carcasses to surface and drift (presuming that they are not covered by sediment; Haberda 1895; Hofmann 1958; Moreno et al. 1992; Petrik et al. 2004; Sorg et al. 1997; Tomita 1975, 1976; Wasmund 1935). Drifting at the water surface, sometimes over months and long distances, carcasses decompose gradually (Giertsen and Morild 1989; Haglund 1993; Schäfer 1972; Smith 2007a; Tomita 1975, 1976; Wild 1978).

Empirical data on the hydrostatic pressure needed to keep a carcass at the sediment surface are available for cetaceans, various terrestrial tetrapods such as humans, mice, and domestic pigs, and different freshwater fish (e.g., Allison et al. 1991; Anderson and Hobischak 2004; Berg 2004; Elder and Smith 1988; Esperante et al. 2008; Moreno et al. 1992; Smith 2007a; Tomita 1975, 1976; Tønnessen and Johnsen 1982). These studies reveal that higher hydrostatic pressures are required to suppress the rise of carcasses of larger dimensions compared to smaller carcasses (e.g., Barton and Wilson 2005; Tomita 1975, 1976; see also Kemp 2001). Apparently, taxonomy does not play a major role in this respect, but physics does (Tomita 1975).

In marine environments, Recent cetaceans and human carcasses may rise from water depths up to 50 m, but never from below 100 m (Tomita 1975, 1976; Tønnessen and Johnsen 1982). The above-mentioned water depth estimate

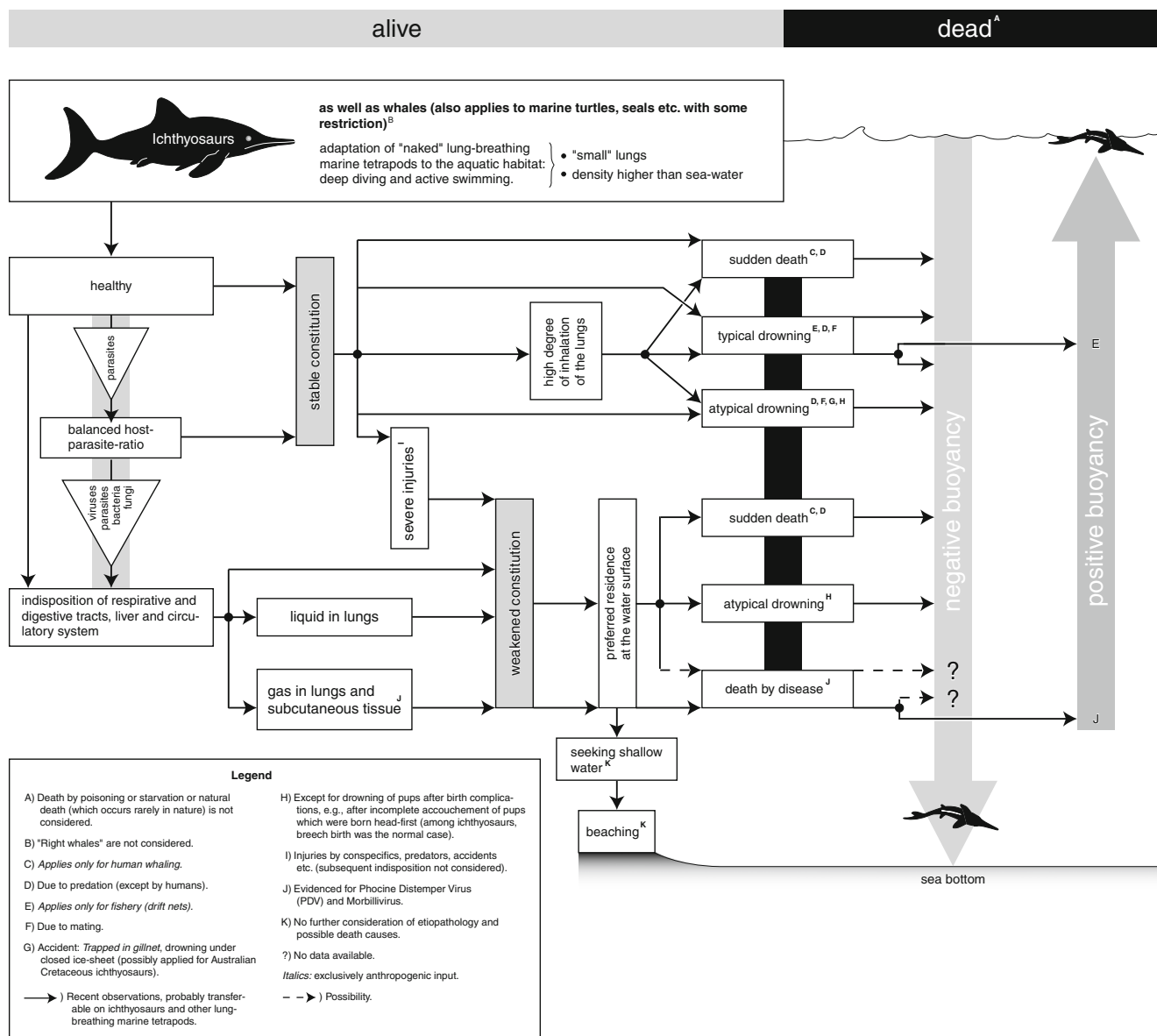


Fig. 4 Peri- and postmortem behavior of marine tetrapods without buoyancy-increasing body fat, oil, hair or feathers in the pelagic realm (modified after Hänggi and Reisdorf 2007; references in Reisdorf 2007)

of the "Posidonienschiefer Formation sea" in southern Germany of 50–150 m (Röhl et al. 2001) matches the physical requirements to keep an ichthyosaur carcass on the seafloor. In the case of nearly complete ichthyosaur skeletons, it is very likely that the carcass was entombed close to the place of death because of the short settling time.

Skeleton preservation as a sea-level proxy?

The taphonomy of lung-breathing tetrapods depends on water depth and, thus, can be used as palaeobathymetrical proxy (cf. Allison et al. 1991). Early Jurassic ichthyosaur remains

display recurring taphonomic patterns which can be grouped into three preservation categories: (1) articulated skeletons, (2) disarticulated skeletons, and (3) isolated bones (e.g., Martill 1986, 1993; isolated body parts of predated animals which sank towards the seafloor are not considered in the subsequent discussion; e.g., Böttcher 1989; Martill 1993; Taylor 2001).

Articulated skeletons are equally abundant and well-documented throughout the Early Toarcian; for instance, >3000 more or less articulated specimens are known just from the Holzmaden area in Germany (Martill 1993; McGowan and Motani 2003). These articulated skeletons are not included in this analysis because these carcasses were apparently largely or completely embedded

in the sediment immediately after grounding while sinking into the “soupy substrate” (Hofmann 1958; Martill 1993; but see Smith and Wuttke 2012, this issue). Adhesion and sediment weight prevented the carcass from surfacing even when putrefaction gases developed sufficiently to lift the carcass (Hofmann 1958; see also Piccard 1961). Additionally, they were protected against Metazoan scavengers (Hofmann 1958) or bottom currents, i.e. the carcasses could not be realigned after their deposition.

Disarticulated skeletons are mainly found in sediments deposited during times of eustatic sea-level rise (=transgressive cycles; e.g., de Graciansky et al. 1998; Hallam 2001) under oxygen-depleted conditions (Hauff 1921; Röhl et al. 2001). Such skeletons were probably not or not completely covered by sediment for a prolonged timespan or they were secondarily exhumed (e.g., Hofmann 1958; Kauffman 1981; Martill 1993). Apparently, rising of the carcasses was prevented by hydrostatic pressure and/or partial sediment cover (Allison et al. 1991; Hofmann 1958; Tomita 1975, 1976). Speculatively, an overgrowth by microbial mats or other organisms might have

had the potential to prevent the carcass from refloatation to the water surface. However, the remarkable completeness of isolated parts of a skeleton found in spatial proximity rules out strong bottom currents.

Isolated bones, scarcity or absence of ichthyosaur fragments result from times of eustatic sea-level fall (=regressive cycles; e.g., de Graciansky et al. 1998; Hallam 2001). Many carcasses surfaced because of the low hydrostatic pressure which allowed putrefaction gases to develop. These skeletons disintegrated while floating (e.g., Hofmann 1958; Martill 1986, 1993). Such isolated bones possibly underwent a further maceration up to complete disintegration.

The “Ichthyosaur Corpse Curve” (ICC; Fig. 5) summarizes the frequency of different modes of ichthyosaur preservation in Central Europe during the Lower Jurassic. The poor correlation of the ichthyosaur record of the Hettangian with the sea-level curve of Hallam (1988, 2001) may be explained by the generally still low sea-level of this interval. The “Ichthyosaur Corpse Curves” are based on data from England, Germany, and Switzerland for which a reasonable amount of well-

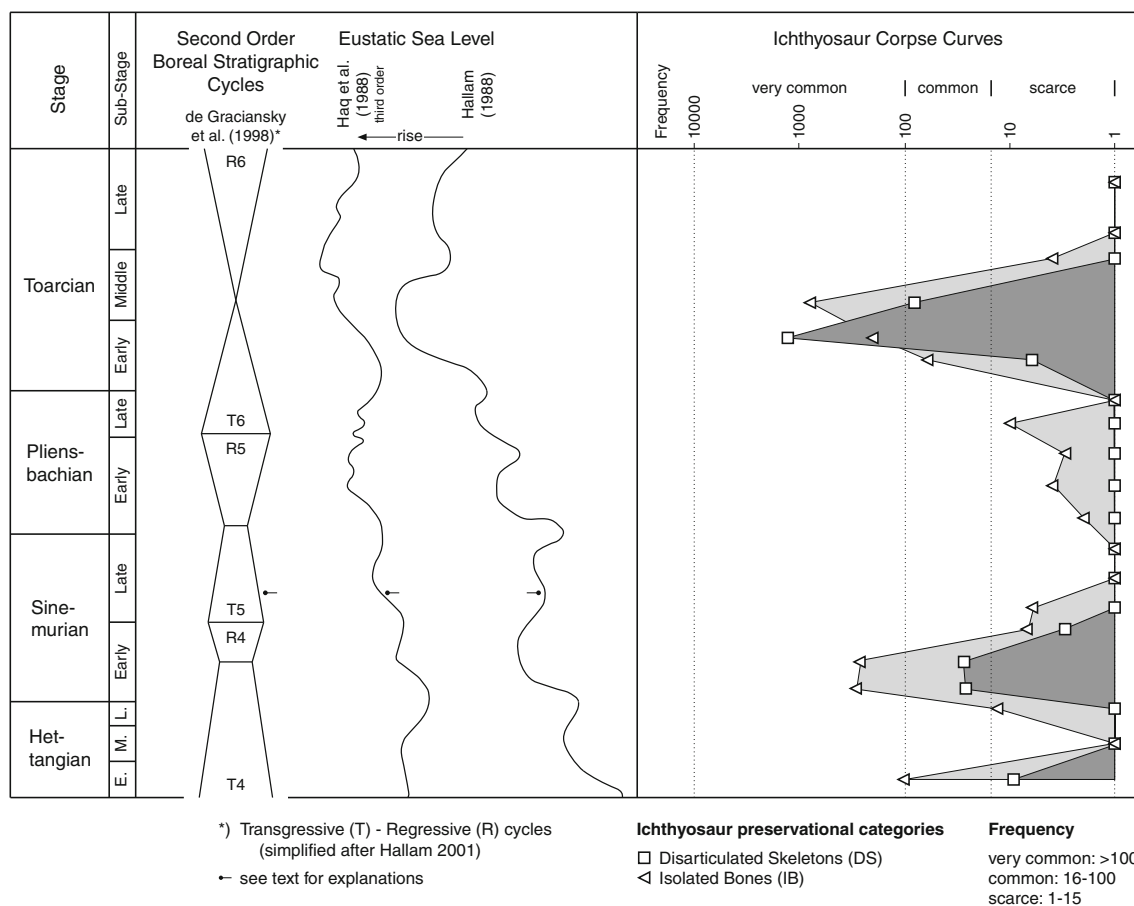


Fig. 5 Taphonomy of Early Jurassic ichthyosaurs from northwestern and central Europe compared to eustatic sea-level curves. Ichthyosaur taphonomy appears to reflect eustatic sea-level changes. A rising or relatively high eustatic sea-level sensu Hallam (2001) appears to favor

rich occurrences of ichthyosaurs (literature data and estimates; see Table 1). At times of low or falling sea-level or low-amplitude rise, ichthyosaur remains are scarce, and preservation of single bones prevails (see Table 1 and main text; see also Hesselbo and Palmer 1992)

documented ichthyosaur remains over a longer time interval is available. These occurrences are plotted on a logarithmic scale to give an impression of the three abundance categories. Absence of fossils was set to one occurrence to make them displayable on the logarithmic scale. Due to the unsatisfying documentation of ichthyosaur finds especially in the nineteenth century, partially caused by a focus on articulated skeletons, we had to guess the number of occurrences in several cases, especially since we chose a temporal resolution on ammonite-zone level. The numbers of disarticulated skeletons (DS) and isolated bones (IB) of the “Ichthyosaur Corpse Curves” represent an estimate of the minimum unless precise numbers from the literature or collections were available. In some cases, we estimated some numbers of IB based on the usual ratio of DS to IB of 1:10 to 1:100. Accordingly, the amount of DS in British fossilagerstätten is based on the number of occurrences of articulated skeletons. The abundance of disarticulated ichthyosaur-remains as shown by the DS:IB ratio thus reflects the fossil record in the Lower Jurassic ammonite zones of Great Britain, southern Germany and northern Switzerland (Table 1).

Stratigraphical resolution is in the range of a few million years spanning 3rd order cycles of Haq et al. (1988) or 2nd order cycles of Hallam (e.g., de Graciansky et al. 1998; Hallam 2001). It appears that ichthyosaur skeletal remains are most abundant in sediments of transgressive cycles and rare in sediments of regressive cycles. Cycle T5 of Haq et al. (e.g., de Graciansky et al. 1998) is poor in ichthyosaur remains, but, by contrast, this interval corresponds to a phase of falling sealevel of Hallam (e.g., Hallam 2001; Fig. 5).

Conclusions and significance

1. According to our measurements and deductions, it is impossible that skeletons of vertebrates become disarticulated with their bones being scattered over a certain area exclusively by the release of putrefaction gases under hydrostatic or atmospheric pressures.
2. There is ample evidence that ichthyosaurs and most other lung-breathing marine tetrapods of comparable mode of life were negatively buoyant. This is

Table 1 These data on the occurrences and abundances of preservational modes (disarticulated skeletons *DS*; and isolated bones *IB*) were obtained from museum collection counts (Paläontologische Forschungs-, Lehr- und Schausammlung am Institut für Geowissenschaften Universität Tübingen, Sammlung am Staatlichen Museum für Naturkunde Stuttgart) and from the literature (Altmann 1965; Benton and Taylor 1984; Benton

and Spencer 1995; Berckhemer 1938; Dean et al. 1961; Delair 1960; Fraas 1891; Hauff 1921; von Huene 1922, 1931; Knitter and Ohmert 1983; Maisch 1999; Maisch and Reisdorf 2006; Maisch et al. 2008; Martin et al. 1986; McGowan 1978; McGowan and Motani 2003; Meyer and Furrer 1995; Pratje 1922; Quenstedt 1858; Reiff 1935; Reisdorf et al. 2011; Schieber 1936); for a comment of the quality of the data, see text

Ammonite zonation sensu Dean et al. (1961)	Stages	Great Britain		Germany		Switzerland		Sum DS	Sum IB
		DS	IB	DS	IB	DS	IB		
<i>levesquei</i>	Toarcian	0	0	0	1	0	0	0	1
<i>thouarsense</i>		0	1	0	0	0	0	0	1
<i>variabilis</i>		0	0	0	4	0	0	0	4
<i>bifrons</i>		61	610	18	180	0	0	79	790
<i>falcifer</i>	Pliensbachian	6	60	1,295	130	2	11	1,303	201
<i>tenuicostatum</i>		0	0	6	60	0	0	6	60
<i>spinatum</i>		0	0	0	1	0	0	0	1
<i>margaritatus</i>		0	0	0	10	0	0	0	10
<i>davoei</i>		0	0	0	3	0	0	0	3
<i>ibex</i>		0	0	1	4	0	0	1	4
<i>jamesoni</i>		0	1	0	0	0	1	0	2
<i>raricostatum</i>	Sinemurian	0	1	0	0	0	0	0	1
<i>oxynotum</i>		0	0	0	0	0	0	0	0
<i>obtusum</i>		1	6	0	0	0	0	1	6
<i>turneri</i>		0	1	3	6	0	0	3	7
<i>semicostatum</i>	Hettangian	25	250	1	6	1	11	27	267
<i>bucklandi</i>		25	250	1	35	0	0	26	285
<i>angulata</i>		0	0	0	11	0	2	0	13
<i>liasicus</i>		0	0	0	1	0	0	0	1
<i>planorbis</i>		9	90	0	12	0	0	9	102

corroborated by the fact that even the density of some of the lightest Recent cetaceans (e.g., harbor porpoise *Phocoena phocoena*) is higher than that previously assumed for the most common European ichthyosaur *Stenopterygius* (Kemp et al. 2006; McLellan et al. 2002; Motani 2001; Reisdorf 2007). Therefore, previous body mass calculations of ichthyosaur bodies, which presume a seawater density of the ichthyosaurs, are too low (Reisdorf 2007).

3. If an ichthyosaur body is assumed to have been negatively buoyant, locomotion models which assume that ichthyosaurs needed to overcome positive buoyancy when diving (e.g., Taylor 1987; McGowan 1992) require re-evaluation. Sleep behavior must also have been adapted for negative buoyancy: ichthyosaurs had to actively surface to respire, as do Cetaceans (e.g., Lyamin et al. 2006; Ridgway 2002; Staunton 2005; Wade 1984).
4. Most of the ichthyosaurs that were not killed by external forces died by drowning when rendered unable to surface, due to diseases, complications during pregnancy and the birth process, or old age (Kastelein et al. 1995; Knieriem and García Hartmann 2001; Reisdorf 2007; Shevill et al. 1967; Slijper 1962; Smith 2007a; Fig. 4). They subsequently sank. This theoretically opens the possibility to apply the “diatom-test” (e.g., Hürlimann et al. 2000) to ichthyosaurs, especially to Cretaceous representatives. These algae and other small particles (e.g., Knieriem and García Hartmann 2001; Möttönen and Nuutila 1977; Yoshimura et al. 1995) can be deposited in bones when lung-breathing vertebrates inhale water when drowning (but see also Kan 1973, and Koseki 1968). However, the possible occurrence of such a “fossil trap” has yet to be analysed.
5. Ichthyosaurs usually settled on the sea-floor without any density increase or buoyancy decrease except for the compression of the body as well as the compression (e.g., Hui 1975) and the dissolution of gas contained in the carcass (e.g., Haglund and Sorg 2002; Kemp 2001; Smith 2007a).
6. Buoyancy-increasing formation of putrefaction gases plays a crucial role with respect to the drift behaviour and fossilization of vertebrate carcasses in shallow marine (and lacustrine) depositional environments. A disarticulated skeleton with bones preserved in spatial proximity helps to estimate palaeobathymetry, because the hydrostatic pressure had to be sufficient to counteract the effects of gas formed by putrefaction (=“Cartesian Diver Effect”). This is also important for the interpretation of marine (and lacustrine) fossilagerstätten (e.g., Beardmore et al. 2012, this issue; Buffetaut 1994; Elder and Smith 1988; Esperante et al. 2008; Hofmann 1958; Hogler 1992; Mancuso and Marsicano 2008; Reisdorf and Wuttke 2012, this issue; Sander 1989; Smith and Wuttke 2012, this issue; Zangerl and Richardson 1963).
7. We suggest the use of the term “ichthyosaur fall” for more or less completely preserved ichthyosaur skeletons. This is in accordance with the established marine biological terms “nekton fall” and “whale fall” (e.g., Smith and Baco 2003), which describe carcasses or skeletons of nektonic organisms which sank through the water column to the seafloor.
8. We found that our newly constructed “Ichthyosaur Corpse Curves” for England, south-western Germany and Switzerland (Fig. 5) correlate well with the global sea-level curve of the Early Jurassic by Hallam (e.g., Hallam 2001), but do not match that of Haq et al. (1988) or de Graciansky et al. (1998). Additional uniformitarian taphonomic studies of modern marine lung-breathing vertebrates are necessary to improve “nekton falls” as a useful palaeobathymetric proxy.
9. Most of the outlined factors and mechanisms affecting the density and maceration of Recent cetaceans and ichthyosaurs in water can be generalised with respect to most lung-breathing marine vertebrates and various land-living tetrapods such as humans, at least with some minor modifications (e.g., Donoghue and Minnigerode 1977; Gray et al. 2007; Tomita 1975, 1976).
10. Our findings have implications for a number of today’s environmental problems and the protection of species: The carcasses of many lung-breathing marine vertebrates, such as those of whales, cannot be observed because most of them will never surface or strand (e.g., Cassoff et al. 2011; Ford et al. 2000; Kirkwood et al. 1997; Moreno et al. 1992; Smith 2007a). Knowledge of postmortem hydrostatic pressure, temperature and scavenging rate conditions in Recent cetaceans and ichthyosaurs can serve as a model for human carcasses (Anderson and Hobischak 2004; Haglund 1993; Hood et al. 2003; Kahana et al. 1999; Moreno et al. 1992; Petrik et al. 2004; Schäfer 1972) and thus be applied to the retrieval of missing humans after disasters (e.g., tsunamis, heavy flooding, cyclones) and crimes from bodies of water (e.g., Blanco Pampin and Lopez-Abajo Rodriguez 2001; Tomita 1975, 1976; Tsokos and Byard 2011).

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Chapter III

Synsedimentary Tectonics

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Evidence for synsedimentary differential tectonic movements in a low-subsidence setting: Early Jurassic in northwestern Switzerland

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Abstract

During the Early Jurassic (lasting ~ 27 Myr) only thin deposits (mostly ca. 30–50 m) of the Staffelegg Formation accumulated in wide parts of NW Switzerland while sea-level rise was in the range of ~ 60 m. Isopach and facies patterns provide clear evidence of differential subsidence while faults that formed in the basement during the late Palaeozoic became reactivated. Orientation of many relative thickness minima and maxima follows faults constituting either the Rhenish Lineament or the North Swiss Permo-Carboniferous Trough. Such pattern is seen on the isopach maps of the Schambelen, Beggingen, Weissenstein, Frick, Fasiswald, Mt. Terri, Breitenmatt, Rickenbach, Rietheim and Gross Wolf members of the Staffelegg Formation, independently upon if the individual lithostratigraphic units are condensed or display somewhat enhanced thickness. Onto a general trend of decreasing thickness to the S, often isopach anomalies of small areal extension are superimposed. They suggest that localized strike-slip movements affected a mosaic of basement blocks. Reactivation of faults in the basement during the Early Jurassic is also evidenced by temporally enhanced hydrothermal activity as documented by chronometric ages of veins and mineral alterations.

Keywords Early Jurassic · Basement · Faults · North-Swiss Permo-Carboniferous Trough · Rhenish Lineament

1 Introduction

NW Switzerland is a classical region for research on Mesozoic sediments. Accordingly, Early Jurassic deposits are in the focus of sedimentological, palaeontological and stratigraphical investigations since the eighteenth century (Reisdorf et al. 2011 and references therein). The Early Jurassic sediments constitute the Staffelegg Formation (Reisdorf et al. 2011). They are often fossiliferous and consist predominantly of terrigenous argillaceous material, calcarenites and some intercalated phosphorite layers. These sediments accumulated in a shallow epicontinental marine setting being located at the transition between the SW part of the Swabian Basin and the SE part of the Paris

Basin (Philippe et al. 1996; Jordan et al. 2008; Reisdorf et al. 2011). The palaeogeographic position is reflected by lithological and palaeontological similarities of chronostratigraphically corresponding deposits in NW Switzerland, SW Germany and E France (de Graciansky et al. 1998; Lathuiliere 2008; Schmid et al. 2008; Reisdorf et al. 2011). These Early Jurassic sediments comprise a chronostratigraphic timespan of 26.9 Myr (Ogg et al. 2016).

The Early Jurassic deposits of NW Switzerland, however, are reduced in thickness when compared to the concomitant successions in neighbouring SE Germany and E France (Fig. 1; e.g., Büchi et al. 1965; Bachmann et al. 1987; Lathuiliere 2008; Rupf and Nitsch 2008). In NW Switzerland, the thickness of the Early Jurassic Staffelegg Formation varies between ~ 25 and ~ 100 m (Müller et al. 1984; Reisdorf et al. 2011). However, two distinct trends in the regional thickness pattern of Early Jurassic sediments are evident: (i) the thickness of the entire Early Jurassic deposits decreases from ~ 100 m in E France to ~ 25 m in NW Switzerland; (ii) from N to S thickness decreases in SW Germany from 90 to 40 m to about 25 m in NW Switzerland (Reisdorf et al. 2011). A numerically high-resolution isopach map of the Early Jurassic deposits

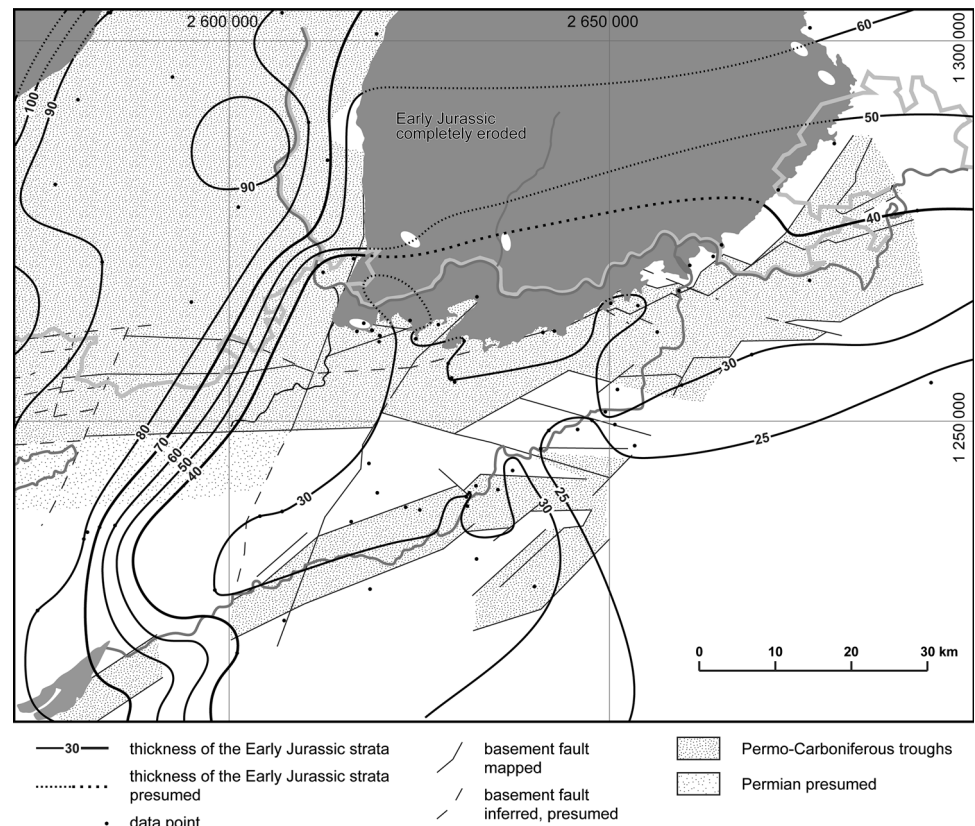
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Fig. 1 Palinspastically restored isopach map of the Early Jurassic in NW Switzerland and adjacent parts of France and Germany (modified after Reisdorf et al. 2011). Contrary to Reisdorf et al. (2011: Fig. 6), the thickness of the basal part of the Opalinus-Ton/Opalinuston Formation (Torulosum subzone, Late Toarcian) is now included



in NW Switzerland does not show considerable variations in thickness within the mentioned trends (cf., Müller et al. 1984; Bitterli 1992; Reisdorf et al. 2011).

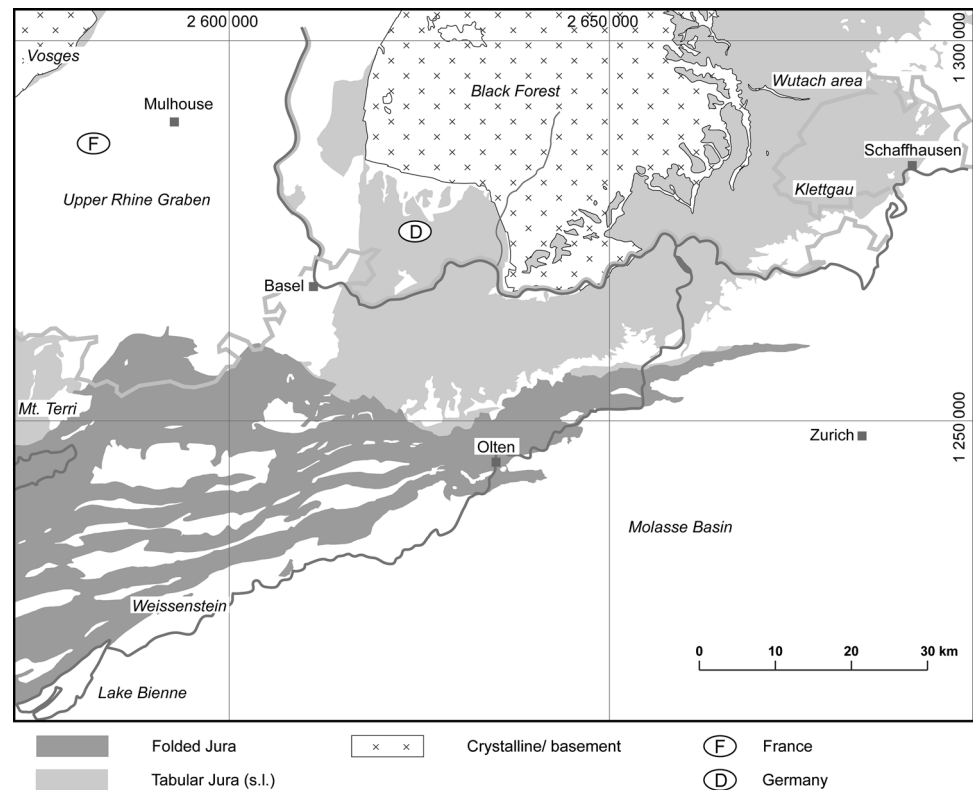
Compared to the chronostratigraphic timespan of 26.9 Myr (Ogg et al. 2016) the low thickness implies an in-average very low net-sedimentation rate of only 0.93–3.72 m/Myr that definitely could have been affected by erosion. These sedimentation rates are two to three orders of magnitude smaller than those that have been calculated for the full marine Middle and Late Jurassic deposits of NW Switzerland (Wetzel et al. 2003). The low sedimentation rates are even intriguing for an epicontinental marine depositional environment, because they are very similar to sedimentation rates of deep sea-sediments in the rock record (cf., Scholle et al. 1983; Füchtbauer 1988). Therefore, it appears that the basin part in NW Switzerland underwent low subsidence. Furthermore, the relatively uniform facies distribution is not suggestive of differential subsidence. Consequently, the accommodation space might have been provided mainly by eustatic sea-level changes (e.g., Brandt 1985; Einsele 1985; Philippe et al. 1996). Thus, the Early Jurassic has been classified as a period of “tectonic quiescence” in NW Switzerland (e.g., Vonderschmitt 1942; Wagner 1953; Laubscher 1986; Thury et al. 1994). In contrast, detailed sedimentological studies during the last decades provided convincing evidence that at least

the southern part of the Central European Epicontinental Basin recurrently experienced phases of considerable differential tectonic subsidence during the Middle and Late Jurassic that modulated sediment-accumulation and affected facies patterns (e.g., Wetzel et al. 1993; Burkhalter 1996; Gonzalez and Wetzel 1996; Wetzel 2000; Allenbach 2002; Wetzel and Allia 2003; Wetzel et al. 2003; Jank et al. 2006). The obvious influence of differential tectonic subsidence on the Middle and Late Jurassic deposits in NW Switzerland leads to the question if the Early Jurassic represents a phase of “tectonic quiescence” or if uniform thickness pattern only obliterates such tectonic effects. It is the purpose of the present study, to analyse thickness and facies pattern in detail and to decipher if and how much the slowly formed lithostratigraphic units of the Early Jurassic Staffelegg Formation were affected by tectonic movements.

2 Study area and geological setting

The study area is located in NW Switzerland and extends into the adjacent regions of E France and SW Germany (Fig. 2). With respect to this study, four tectonic domains are distinguished, Tabular Jura, Folded Jura, Black Forest and Vosges (representing the exhumed Palaeozoic

Fig. 2 Geological overview of the study area, situated in NW Switzerland, SW Germany and E France



basement), and the Cenozoic Upper Rhine Graben that, however, has late Palaeozoic preceding structural elements.

The Palaeozoic crystalline basement is dissected by numerous faults that formed during the late Palaeozoic, in particular when a mega-shear zone developed at the end of the Variscan orogeny between the Ural and the Appalachians (Arthaud and Matte 1977). Numerous basins, grabens, and half-grabens developed, including the so-called “Burgundy Trough” and the “North-Swiss Permo-Carboniferous Trough” including the so-called “Constance-Frick Trough”, “Olten Trough” and “Klettgau Trough” (Fig. 3; Diebold 1988; Ménard and Molnar 1988; Ziegler 1990; von Raumer 1998). In the southernmost Upper Rhine Graben area, a narrow horst occurs that separates the Burgundy and Constance-Frick Trough (Ustaszewski et al. 2005). A large part of the Burgundy Trough terminates to the E at the NE–SW to N–S-trending so-called “Wehra–Zeiningen fault zone” (e.g., Gonzalez 1990; Ustaszewski et al. 2005; Grimmer et al. 2017). Furthermore, at the position of the future Upper Rhine Graben, a roughly N–S-trending fault system comprising the so-called “Rhenish Lineament” established at the end of Variscan orogeny (Boigk and Schöneich 1974; Krohe 1996; Grimmer et al. 2017). The Rhenish Lineament and similarly aligned faults such as the so-called “Caquerelle Fault” continue S of the southern border of the modern Upper Rhine Graben (Liniger 1967; Nussbaum et al. 2017).

These late Palaeozoic tectonic structures are preferentially oriented exhibiting three main strike-directions (Fig. 3; e.g., Einsele and Schönenberg 1964; Wetzel 2008; Geyer et al. 2011): (i) NW–SE (“Herzynian”; 120° – 130°), (ii) ENE–WSW (“Erzgebirgian”; 70° – 80°), and (iii) NNE–SSW (“Rhenish”; 10° – 20°).

In the study area and to the South underneath the Molasse Basin, these basement structures are fairly well known from seismic records (e.g., Diebold et al. 1991; NAGRA 2008; Naef and Madritsch 2014). In contrast, in the Black Forest and the Vosges, corresponding tectonic structures are exposed (e.g., Metz 1977; Zeh 2008 and references therein; Geyer et al. 2011). Depending on the stress field, these tectonic structures became recurrently reactivated during the Mesozoic and Cenozoic as evidenced by vein mineralization and alteration of minerals (e.g., Wernicke and Lippolt 1997; Wetzel et al. 2003; Edel et al. 2007; Staude et al. 2012; Pfaff et al. 2009; Brockamp et al. 2015; Burisch et al. 2016; Walter et al. 2017).

After the Variscan orogeny and late Palaeozoic fault-tectonic phase, during the Triassic wide parts of Central Europe subsided and peneplanation took place. First, terrestrial sediments accumulated until the Middle Triassic, when marine transgression commenced and a shallow epicontinental sea formed (e.g., Feist-Burkhardt et al. 2008; Geyer et al. 2011). In the study area, mainly carbonates, marls and up to ~ 100 m thick evaporites formed

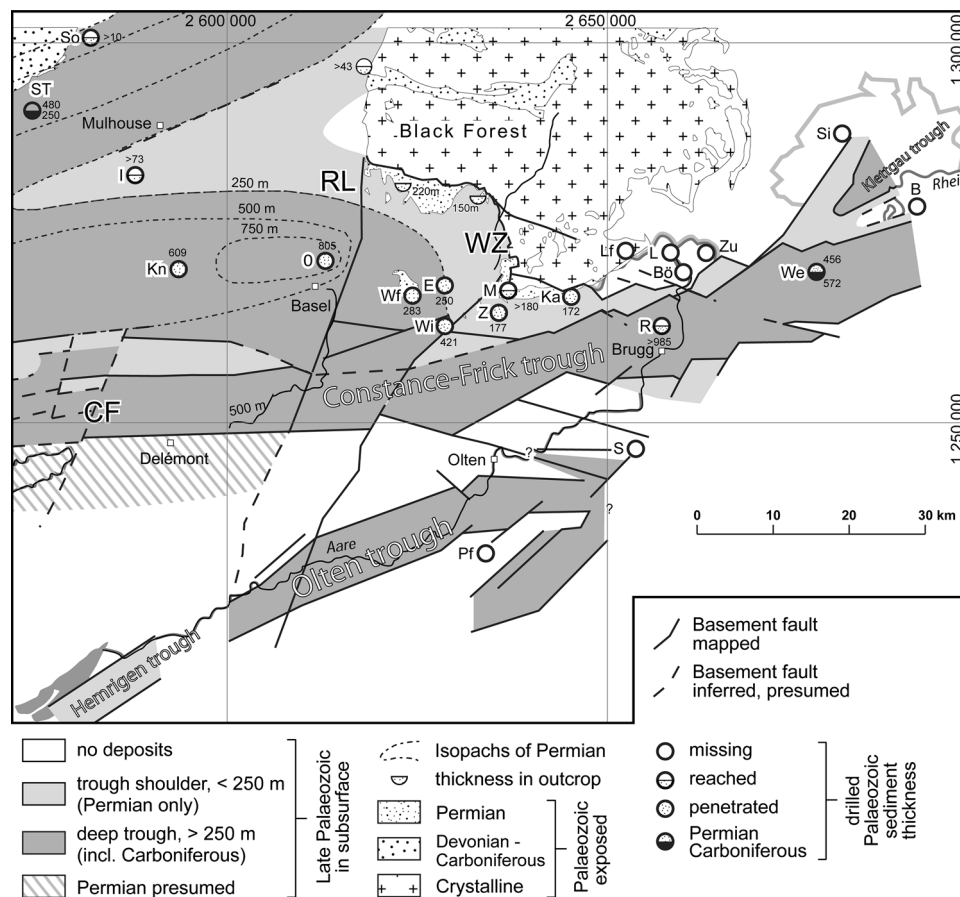


Fig. 3 Known Permo-Carboniferous troughs and faults in NW Switzerland and adjacent parts of France and Germany; modified after Wetzel (2008, but see slightly different interpretation of seismic data by Naef and Madritsch 2014). Abbreviations: CF Caquerelle Fault, RL Rhenish Lineament, WZ Wehra-Zeiningen fault zone, B Benken (NAGRA 2001), Bö Böttstein (NAGRA 1985), Bi Bisel (unpublished), Bx Buix (Schmidt et al. 1924), E Engerfelden (Ryf 1984), I Illfurth (unpublished), K Kaisten (NAGRA 1991), Kn Knorrrinque (unpublished), L Leuggern (Peters et al. 1989), Lf

Laufenburg (Heusser 1926), M Mumpf (Schmassmann and Bayramgil 1946), O Otterbach (Häring 2002), Pf Pfaffnau (Büchi et al. 1965), R Riniken (Matter et al. 1987), S Schafisheim (Matter et al. 1988a), Si Siblingen (NAGRA 1993), So Soultz (unpublished), ST south of Thann (Fluck et al. 1980), We Weiach (Matter et al. 1988b), Wf Weiherfeld (Schmassmann and Bayramgil 1946), Wi Wintersingen (Schmassmann and Bayramgil 1946), Z Zuzgen (Schmassmann and Bayramgil 1946), Zu Zurzach (Cadisch 1956)

under restricted marine conditions (e.g., Philippe et al. 1996; Jordan 2016; Pietsch et al. 2016).

During the Late Triassic (Keuper), continental and marine-marginal conditions repeatedly alternated in the study area (e.g., Jordan 2008; Geyer et al. 2011; Jordan et al. 2016). Furthermore, during the Late Triassic sediment accumulation was recurrently interrupted for prolonged periods of time as evidenced by paleosols of various maturity and regional as well as basin-wide unconformities (e.g., Etzold and Schweizer 2005; Nitsch et al. 2005). Consequently, net-sedimentation rates were rather low being in the range of 7–9 m/Myr (Nitsch et al. 2005). During the Early Jurassic, sedimentation rates further decreased in NW-Switzerland to 0.93–3.72 m/Myr for this period as a whole (see above). In fact, from Early Triassic to Early Jurassic subsidence shows a roughly exponential decrease (e.g., Loup 1992; Wetzel et al. 2003).

For the latest Triassic (Rhaetian) in the study area, three regional and basin-wide unconformities have been recognized (e.g., Etzold and Schweizer 2005; Nitsch et al. 2005). The Rhaetian sediments formed in an estuarine to (marginal-)marine setting close to sea-level as evidenced by stagnant pore water and dolomite layers (Beutler and Nitsch 2005; Geyer et al. 2011; Fischer et al. 2012; Jordan et al. 2016; Schneebeili-Hermann et al. 2018). In spite of the long time span of the Rhaetian (4.7 Myr; Ogg et al. 2016), the sediment record is rather incomplete while widely affected by erosion in a roughly N–S trending area (e.g., Etzold and Schweizer 2005 and references therein; Reisdorf et al. 2011; Jordan et al. 2016). The uppermost unconformity developed at the latest during the transgression in Early Jurassic times (e.g., Hallam 2001; Etzold and Schweizer 2005; Reisdorf et al. 2011 and references therein).

The Jurassic transgression is related to the disintegration of Pangea as well as the opening of the Tethys to the South and of the North Atlantic to the West (e.g., Ziegler 1990; Stollhofen et al. 2008). Thereafter throughout the Jurassic, an epicontinental sea covered major parts of central Europe (Central European Epeiric Sea; e.g., Ziegler 1990; Smith et al. 2004; Pieńkowski et al. 2008). However, to the East, the southern part of the basin was bounded by the Bohemian Massif and to the South by the Alemannic Land (Fig. 4; e.g., Stoll-Steffer 1987; Loup 1993; Jordan et al. 2008; Geyer et al. 2011). The latter was quite close to the study area (e.g., Jordan et al. 2008). During the Early Jurassic, the study area was situated in the boreal realm at latitude of approximately 35° to 40°N (Ziegler 1988; Edel 1997; Smith et al. 2004).

Independent on lithology and strata arrangement, the Early Jurassic deposits of NW Switzerland, SW Germany and E France show numerous correlative erosional unconformities and reworking horizons (Bessereau and Guillocheau 1994; de Graciansky et al. 1998; Bloos et al. 2005; Reisdorf et al. 2011; STG 2016). In the thin Early Jurassic deposits of NW Switzerland, erosional unconformities are more clearly developed and they erode stratigraphically deeper than in adjacent areas towards the W, N, or E, which are characterised by thicker sediments (Fig. 5).

Distinct facies changes over short distance occur in NW Switzerland and lithostratigraphic units exhibit pronounced facies variations. This is in particular true for the Sinemurian deposits in the Folded Jura and to the south in the Molasse Basin (Reisdorf et al. 2011).

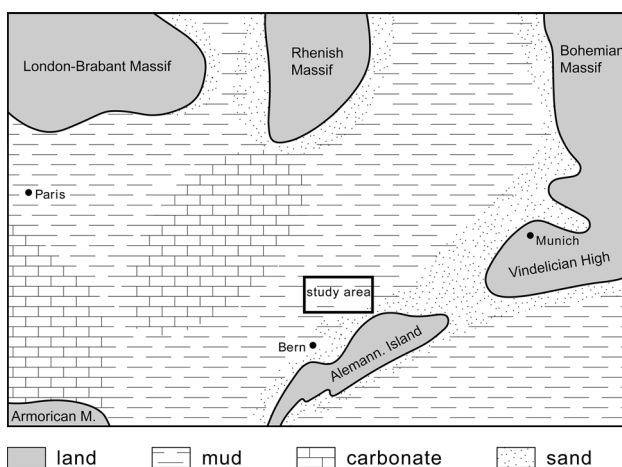


Fig. 4 Paleogeographic map for the Early Jurassic in NW Switzerland and adjacent parts of France and Germany. The study area was covered by shallow epicontinental sea (modified after Ziegler 1990; Wetzel and Reisdorf 2007)

3 Materials and methods

The deposits studied almost completely cover the Early Jurassic. Since no chronometric age data are available the time frame is based on biostratigraphic data, which are correlated with the Jurassic Time Scale of Ogg et al. (2016). The biostratigraphic sub-division of the Early Jurassic follows the European standard ammonite biostratigraphy, which distinguishes Boreal and Tethyan ammonite zonation (e.g., de Graciansky et al. 1998; Pieńkowski et al. 2008). For this study, the ammonite zonation of the Boreal realm is utilised (e.g., de Graciansky et al. 1998; Pieńkowski et al. 2008). For the onset of the Early Jurassic, there is a difference of ~ 0.3 Myr between Boreal (201.4 Ma) and Tethyan realm (~ 201.1 Ma), while the boundary between the Early and Middle Jurassic is bio- and chronostratigraphically consistent in the Boreal and Tethyan ammonite zonation (Cresta et al. 2001; Hillebrandt et al. 2013; Ogg et al. 2016). The *Torulolum* subzone, previously attributed by many authors to the Middle Jurassic *Opalinum* zone, belongs to the *Aalensis* zone and, therefore, represents the latest Early Jurassic (Schmid et al. 2008; Feist-Burkhardt and Pross 2010; Reisdorf et al. 2014). The Early–Middle Jurassic boundary is dated to an age of 174.2 Ma (Ogg et al. 2016).

The age of lithostratigraphic units is given in chronostratigraphic terminology (e.g., “Early” instead of “Lower”) following the recommendation of the Swiss Committee of Stratigraphy (Remane et al. 2005). The lithostratigraphic classification follows the nomenclature used in the E and SE of France, SE Germany and NW Switzerland (Fig. 5). Lithostratigraphic boundaries do not coincide, but in rare cases are approximate to chronostratigraphic boundaries (e.g., stages and substages; de Graciansky et al. 1998; Bloos et al. 2005; Reisdorf et al. 2011; Morard et al. 2014). Marker beds of the Hettangian and Early Sinemurian (Hallau Bed, Schleithem Bed, Gächlingen Bed, Oolithenbank, Kupferfelsbank; Fig. 5) as well as the topmost interval of the Early Pliensbachian comprising Trasadingen Bed, Davoei-Bank and Banc à Davoei was used for the preparation of isopach maps (see below).

Isopach maps show the spatial thickness distribution of sedimentary bodies. In combination with additional data morphology of the depositional area as well as subsidence pattern can be deciphered (e.g., Wetzel et al. 1993; Wetzel and Allia 2003; Allenbach and Wetzel 2006). The isopach maps comprise facies variations within the lithostratigraphic units. Delimitation of the facies changes are shown in the respective maps.

The isopach maps of the study are based on ca. 1700 published and unpublished thickness data (for details see

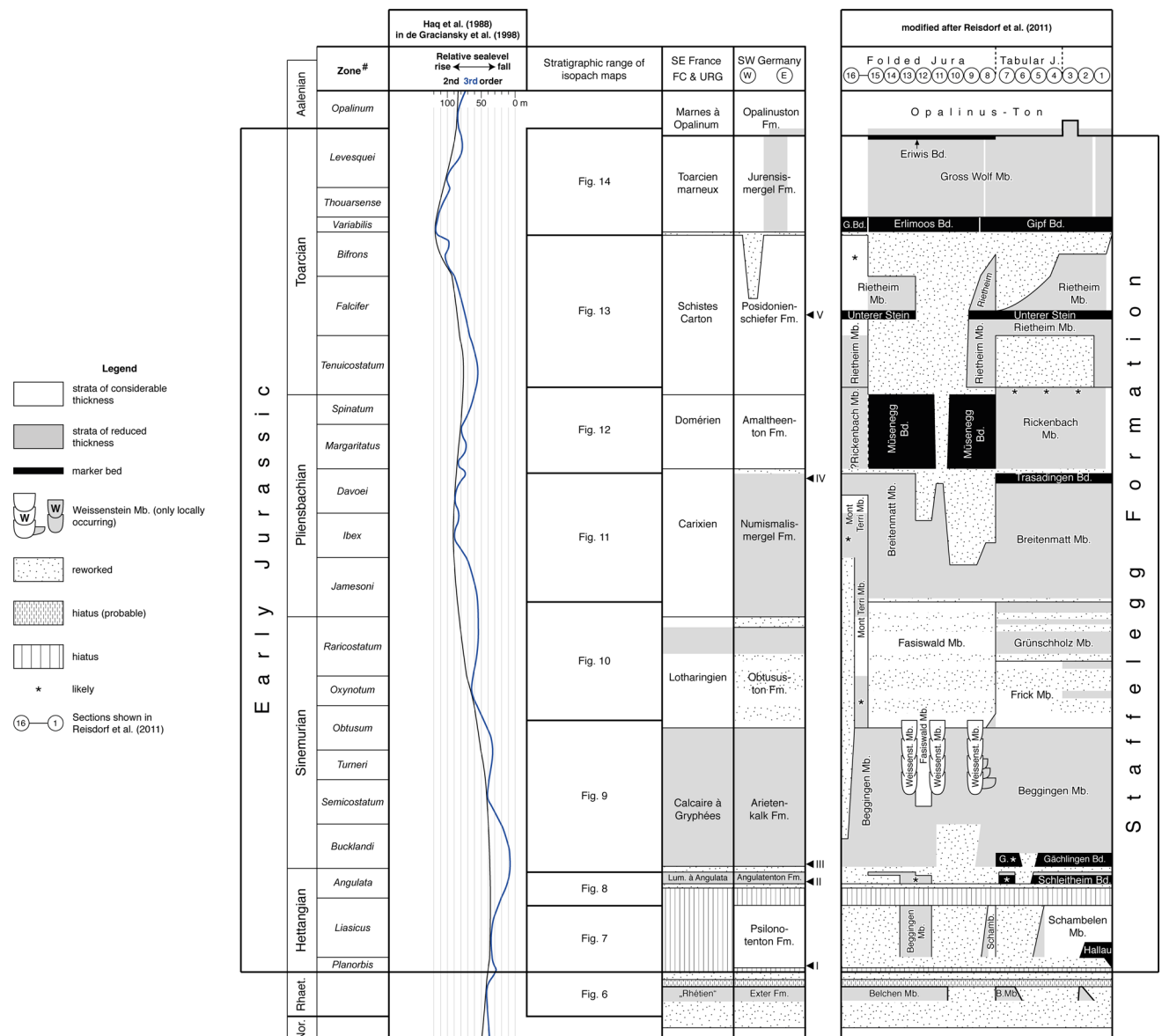


Fig. 5 Early Jurassic biostratigraphy and lithostratigraphy of NW Switzerland and adjacent parts of SW Germany and E France as well as eustatic sea-level change during this period of time (compiled from Haq et al. 1988 and Reisdorf et al. 2011; modified). Note the stratigraphic range of the isopach maps. Due to the partly complex stratigraphic architecture of the Early Jurassic deposits in a few cases simplifications are required in the assignment of lithostratigraphic units: (i) despite of its wide chronostratigraphical range, the Weissenstein Member is included in only one isopach map; (ii) the thickness values for the Mt. Terri Member based on the biostratigraphic data available are incorporated into two isopach maps. *B.Mb*

Belchen Member, *E* East of the Black Forest, *FC* France Comté, *Fm.* Formation, *G.* Gächlingen Bed, *G.Bd.* Gipf Bed?, *Lum.* Lumachelle, *Mb.* Member, *Nor.* Norian, *Rhaet.* Rhaetian, *Schamb.* Schambelen Member, *Tabular J.* Tabular Jura, *URG* Upper Rhine Graben, *W* West of the Black Forest, *#* = zones sensu Dean et al. (1961), sensu Bloos (1979) and sensu Schlegelmilch (1992); I = Pilonotenbank (e.g., Bloos et al. 2005; Etzold et al. 2010); II = Oolithenbank (e.g., Schloz 1972; Bloos et al. 2005; Schmid et al. 2008); III = Kupferfelsbank (e.g., LGRB 2004; Schmid et al. 2008); IV = Davoei-Bank (e.g., Schlatter 1991); V = Unterer Stein (e.g., Urlichs 1977; Röhl and Schmid-Röhl 2005)

online supplemental material). No references to data points are given in the description and captions of the isopach maps, but they are provided in the online supplemental material. Locations or geographic domains are given in today's terms, even if they might not have existed during the Early Jurassic,

such as the Black Forest, Tabular and Folded Jura or Upper Rhine Graben. Isopachs were drawn by linear interpolation between data points. Compensating for the increasing shorting of the Folded Jura to the west, data points today situated within the Folded Jura were palinspastically restored

by counterclockwise rotation around a point at the eastern tip of the Folded Jura at the Lägern by 7°–8° to locate them at their original position during deposition (see Laubscher 1965, 1986; Kempf et al. 1998).

The depositional water depth was estimated. For the Central European Epicontinental Basin the fair-weather wave base has been stated to have been located in ~ 5–10 m and the storm wave base at ~ 30 m (Einsele 1985; Brandt 1985; Wetzel and Allia 2003). Furthermore empirical values gained from forensic and marine biological studies imply a water depth range of up to > 50 m (Reisdorf et al. 2012 and references therein).

To decipher effects of synsedimentary subsidence, besides sea-level changes and depositional water depth, the initial sediment thickness needs to be known. Therefore actual thickness is multiplied with so-called “decompaction factor” (e.g., Einsele 2000) that is at the given overburden 2 for mudstone, 1.6 for sandstone and 1.5 for limestone. The thickness of the individual lithostratigraphic units in compacted and decompacted state are listed in Tables 1, 2, 3.

4 Isopach maps

Based on the biostratigraphic framework the isopach maps have a resolution of approximately one sub-stage. The isopach maps form the base to unravel subsidence pattern and to decipher related facies changes.

4.1 Belchen Member (Rhaetian, Late Triassic)

For the Rhaetian, the sandstone and the mudstone facies have not been distinguished in the isopach map (Fig. 6). Three areas can be recognised from E to W:

- In the East sediments up to 2.4 m are found (this occurrence is not clearly demarcated because of lacking data).
- South of the Black Forest, no Rhaetian sediments are preserved.
- West of the Black Forest sediments reach a thickness up to 10 m.

Due to the abundant outcrops and their spatial distribution in the western part of the study area, the thickness pattern can be more differentiated than towards the east. Three localised relative thickness maxima are evident from section and well data: (i) in the centre of the Upper Rhine Graben, (ii) SW of the Black Forest in a narrow area in the Tabular Jura (Dinkelberg) and the Upper Rhine Graben, and (iii) in the Molasse Basin south of the Folded Jura (well Pfaffnau). Except for these relative maxima in thickness, the Rhaetian sediments are ~ 5 m thick.

4.2 Schambelen Member and base of the Beggingen Member (Early Hettangian, Early Jurassic)

The Beggingen Member has a diachronous base, and, hence, is addressed separately for the Early and Late Hettangian as well as the Sinemurian. Early Hettangian sediments occur within two-thirds of the study area (Fig. 7). Because of the low number of data points around the Black Forest, the thickness pattern is subjected to some uncertainty there. South of the Black Forest a distinct isopach pattern is documented by the 1-m line that trends N–S, but in the south of the study area, it becomes ENE–WSW directed and thus, parallel to the limit of the Early Hettangian deposits. Deposits < 1 m thick constitute an irregularly demarcated area.

South of today's Black Forest between Brugg and Schafisheim a pronounced W–E directed increase in thickness culminates in a regional thickness maximum of ~ 9 m. From there, thickness decreases to the east to > 4 m. Due to the lack of data it cannot be proven whether the W–E trending thickness gradient continues in the southern part of the study area. Another regional thickness maximum of ~ 9 m is located in the Wutach area east the Black Forest (Wutach area). It is N–S-oriented. These two depocenters are aligned in Rhenish direction.

4.3 Base of the Beggingen Member (Late Hettangian)

In NW Switzerland, SW Germany and SE France, the late Hettangian is characterized by deposits of low thickness (Contini 1984; Geyer et al. 2003, 2011; Reisdorf et al. 2011). In wide parts, thickness is > 2 m (Fig. 8). In the southern part, no sediments of this age are present in an elongated W–E to SW–NE trending area. The overlying deposits indicate reworking at their base (Reisdorf et al. 2011). Another, but small area lacking Late Hettangian sediments is located SW of the Black Forest near Arisdorf. Isopachs are roughly E–W oriented while thickness tends to decrease southward. At the eastern limit of the study area, a W–E oriented trend of increasing thicknesses is seen.

4.4 Beggingen Member and Weissenstein Member (Early Sinemurian–early Late Sinemurian)

These Early Sinemurian–early Late Sinemurian sediments cover for the first time in the Early Jurassic the study area entirely (Fig. 9). Narrowly spaced and interfingering

Table 1 Thickness of lithostratigraphic units of the Latest Triassic and Early Jurassic in NW Switzerland

Formation (Fm.)/Member (Mb.)	Thickness compacted [m]	Thickness decompact [m]	Sedimentation Rate [m/Myr] compacted sediment	Sedimentation Rate [m/Myr] decompact sediment	Decompaction Factor	Ammonite Zone	Age [Myr]	Duration [Myr]
Gross Wolf Mb. and lower part Opalinus-Ton	0.4–42.9	0.9–85.8	0.1–10.7	0.9–85.8	2	Variabilis–Aalensis	178.2–174.2	4
Rietheim Mb.	0–19.5	0–39.0	0–3.6	0–39.0	2	Tenuicostatum–Bifrons	183.6–178.2	5.4
Rickenbach Mb./Breitenmatt Mb. (only Müsenegg Bd.)	0–c. 3.0	0–6.0	0–0.6	0–6	2	Margaritatus–Tenuicostatum	188.3–183.6	4.7
Breitenmatt Mb. (excl. Müsenegg Bd.)/upper part Mt. Terri Mb.	0.5–c. 9.5	0.8–14.3	0.2–> 3.5	0.8–14.3	1.5	Jamesoni–Davoei	191.0–188.3	2.7
Frick Mb. & Grünschoholz Mb./Fasiswald Mb./lower part Mt. Terri Mb.	0?; 2.5–27.0	0?; 5.0–54.0	0?; 0.6–6.9	0?; 5.0–54.0	2	Obtusus–Jamesoni	194.9–191.0	3.9
upper part Beggingen Mb. and Weissenstein Mb.	1.5–24.4	2.3–36.6	0.33–5.4	2.3–36.6	1.5	Bucklandi–Obtusus	199.4–194.9	4.5
lower part Beggingen Mb.	0–c. 3.0	0–4.5	0–4.3	0–4.5	1.5	Angulata	200.1–199.4	0.7
Schambelen Mb./base Beggingen Mb.	0–9.1	0–18.1	0–9.1	0–18.1	2	Planorbis–Liasicus	201.1–200.1	1
Belchen Mb. (Kletgau Fm.)	0–7.0 (10.0?)	0–11.2 (16.0?)	0–0.8 (1.2?)	0–11.2 (16)	1.6	/	209.6–201.1 (205.8–201.1)	8.5 (4.7)

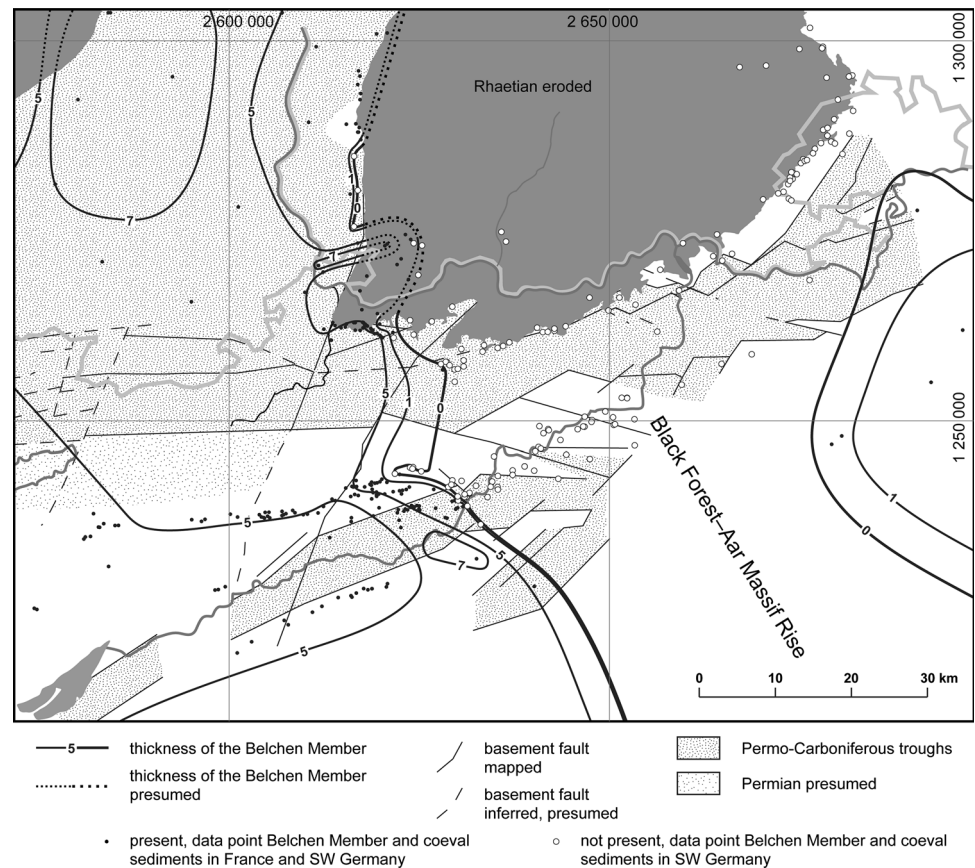
Table 2 Thickness of lithostratigraphic units of the Latest Triassic and Early Jurassic in E France and SW Germany (today's Upper Rhine Graben)

Formation (Fm.)	Thickness compacted [m]	Thickness decompact [m]	Sedimentation Rate [m/Myr] compacted sediment	Sedimentation Rate [m/Myr] decompact sediment	Decompaction Factor	Ammonite Zone	Age [Myr]	Duration [Myr]
Jurensismergel Fm. and Opalinuston Fm.	3.0–39.0	6.0–78.0	0.7–9.8	1.5–19.5	2	Variabilis–Aalensis	178.2–174.2	4
Posidonienschiefer Fm.	3.0?–12.0	6.0–24.0	0.6–2.2	1.1–4.4	2	Tenuicostatum–Bifrons	183.6–178.2	5.4
Amaltheenton Fm.	3.5–c. 30.0	7.0–60.0	0.7–6.4	1.5–12.8	2	Margaritatus–Tenuicostatum	188.3–183.6	4.7
Numismalismergel Fm.	c. 0.7–c. 25.0	1.3–50.0	0.2–9.3	0.5–18.5	2	Jamesoni–Davoei	191.0–188.3	2.7
Obtususton Fm.	22.0–30.7	44.0–61.4	5.6–7.9	11.3–15.7	2	Obtusum–Jamesoni	194.9–191.0	3.9
Arietenkalk Fm.	<3.0–> 5.0	<4.5–> 7.5	0.7–1.1	1.0–1.7	1.5	Bucklandi–Obtusum	199.4–194.9	4.5
Angulatenton Fm.	c. 0.5–2.5	0.8–3.8	0.7–3.6	1.1–5.4	1.5	Angulata	200.1–199.4	0.7
Pylonotenton Fm.	0	0	0	0	2	Planorbis–Liasicus	201.1–200.1	1
Early Jurassic	40.0–90.0	/	1.5–3.3	/	/	Planorbis–Aalensis	201.1–174.2	27
Exter Fm.	2.0–10.0	3.2–16.0	0.2–1.2	0.4–1.9	1.6	/	209.6–201.1 (205.8–201.1)	8.5 (4.7)

Table 3 Thicknesses of lithostratigraphic units of the Latest Triassic and Early Jurassic in SW Germany

Formation (Fm.)	Thickness compacted [m]	Thickness decompacted [m]	Sedimentation Rate [m/Myr] compacted sediment	Sedimentation Rate [m/Myr] decompacted sediment	Decompaction Factor	Ammonite Zone	Age [Myr]	Duration [Myr]
Jurensismergel Fm. and Opalinuston Fm.	1.8–8.0	3.6–16.0	0.5–2.0	0.9–4.0	2	Variabilis–Aalensis	178.2–174.2	4
Posidonienschiefer Fm.	1.7–12.4	3.3–24.9	0.3–2.3	0.6–4.6	2	Tenuicostatum–Bifrons	183.6–178.2	5.4
Amaltheenton Fm.	1.6–10.2	3.1–20.4	0.3–2.2	0.7–4.3	2	Margaritatus–Tenuicostatum	188.3–183.6	4.7
Numismalismergel Fm.	0.7–3.0	1.4–6.0	0.3–1.1	0.5–2.2	2	Jamesoni–Davoei	191.0–188.3	2.7
Obtususton Fm.	15.0–25.0	30.0–50.0	3.9–6.4	5.9–12.8	2	Obtusum–Jamesoni	194.9–191.0	3.9
Arietenkalk Fm.	2.6–c. 6.0	3.9–9.0	0.6–1.3	0.9–1.2	1.5	Bucklandi–Obtusum	199.4–194.9	4.5
Angulatenton Fm.	0.4–2.0	0.6–3.0	0.6–2.9	0.9–4.3	1.5	Angulata	200.1–199.4	0.7
Pylonotenton Fm.	0–9.1	0–18.2	0–9.1	0–18.2	2	Planorbis–Liasicus	201.1–200.1	1
Early Jurassic	36.0–c. 65.0	/	1.3–2.4	/	/	Planorbis–Aalensis	201.1–174.2	27
Exter Fm.	0–8.5	0–13.6	0–1.0	0–1.6	1.6	/	209.6–201.1 (205.8–201.1)	8.5 (4.7)

Fig. 6 Palinspastically restored isopach map of the Belchen Member (Klettgau Formation), Exter Formation and Argilies et grés rhétiens or „Rhétien“, respectively; Rhaetian (Late Triassic). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)



different facies lead to a more complexly structured isopach pattern in the southern part than in the northern part.

The isopach map comprises mainly condensed arenitic limestone (Lithofacies A) and calcareous sandstone and sandy limestone (Lithofacies B). Lithofacies A dominates the Beggingen Member, while the Weissenstein Member mainly constitutes Lithofacies B. Addressing both lithostratigraphic units separately reveals considerable thickness differences between them.

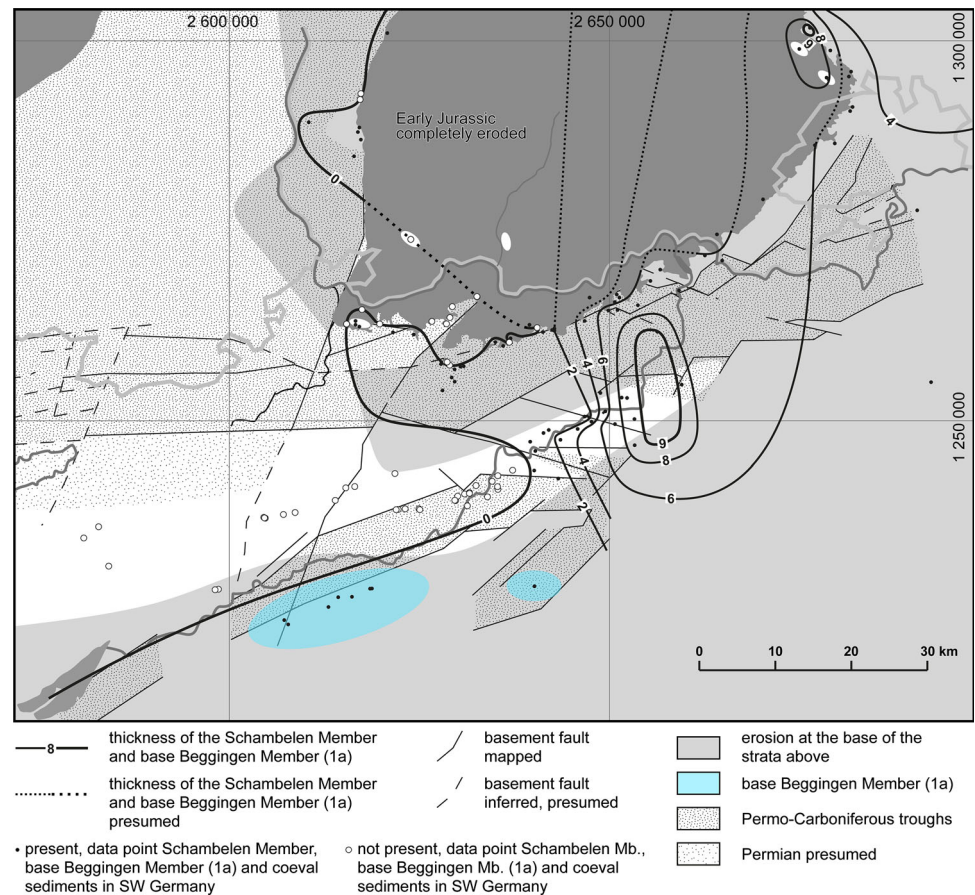
The isopach map of Lithofacies A shows two domains. In the N, higher thickness of 3 to > 5 m tending to increase to the N occur on both sides of the Black Forest (Wutach area and Upper Rhine Graben) than at its immediate margin, where thickness is between 2 and 3 m. Because of the low number and poor quality of data in the Upper Rhine Graben area, the course of isopachs is rather uncertain. S of the Black Forest, but presumably also to the S of the Upper Rhine Graben, Lithofacies A still exhibits low thickness. In the southern part of study area, Lithofacies A reaches ~ 5 m thickness only in the SW (Weissenstein area). Thickness tends to decrease from ~ 5 to > 1 m from S to N. In the SE, however, several local minima (< 1 m) and maxima (> 4 m) follow a SW-NE orientation superimposed on a background value of > 1 m.

The Weissenstein Member (Lithofacies B) is restricted to the southern part of the study area; its thickness decreases from S to N. Isopachs > 5 m are tongue-shaped and S–N-directed. Several maxima > 5 m and up to 22.5 m thick occur. Because of the facies interfingering (see above), the isopachs of the Weissenstein Member overlap those of Lithofacies A. The thickness maxima of the Weissenstein Member coincide with those of the Beggingen Member only in the SW of the study area (Weissenstein area).

4.5 Frick Member, Grünschholz Member, Fasiswald Member and basal part of the Mt. Terri Member (early Late Sinemurian–Early Pliensbachian)

These members are summarised in one isopach map. In the NW of the study area, a wide, N–S oriented depocenter (≥ 25 m) is developed, which is largely limited to the today's Upper Rhine Graben (Fig. 10). In the borehole Sierenz, the largest thickness of ~ 30 m occurs. Towards the E, thickness decreases markedly and in the Klettgau area near Beggingen, it reaches a minimum of 9 m.

Fig. 7 Palinspastically restored isopach map of the Schambelen Member and base of the Beggingen Member (Staffelegg Formation), Psilonotenton Formation; Early Hettangian (Early Jurassic). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)



South of the Upper Rhine Graben and the Black Forest, deposits are 15–20 m thick. This thickness decreases from N to S to < 10 m in the southernmost part of the study area matching the general trend that, however, is opposed by two local thickness maxima > 15 m. They are aligned in NE–SW direction and exhibit thicknesses ~ 19 m and ~ 25–27 m, respectively. In the Mt. Terri region thickness strongly decreases as the basal Mt. Terri Member thins from ~ 10 m to 0 m over a short distance (Fig. 10; Reisdorf et al. 2011).

4.6 Breitenmatt Member and upper part of the Mt. Terri Member (early Pliensbachian)

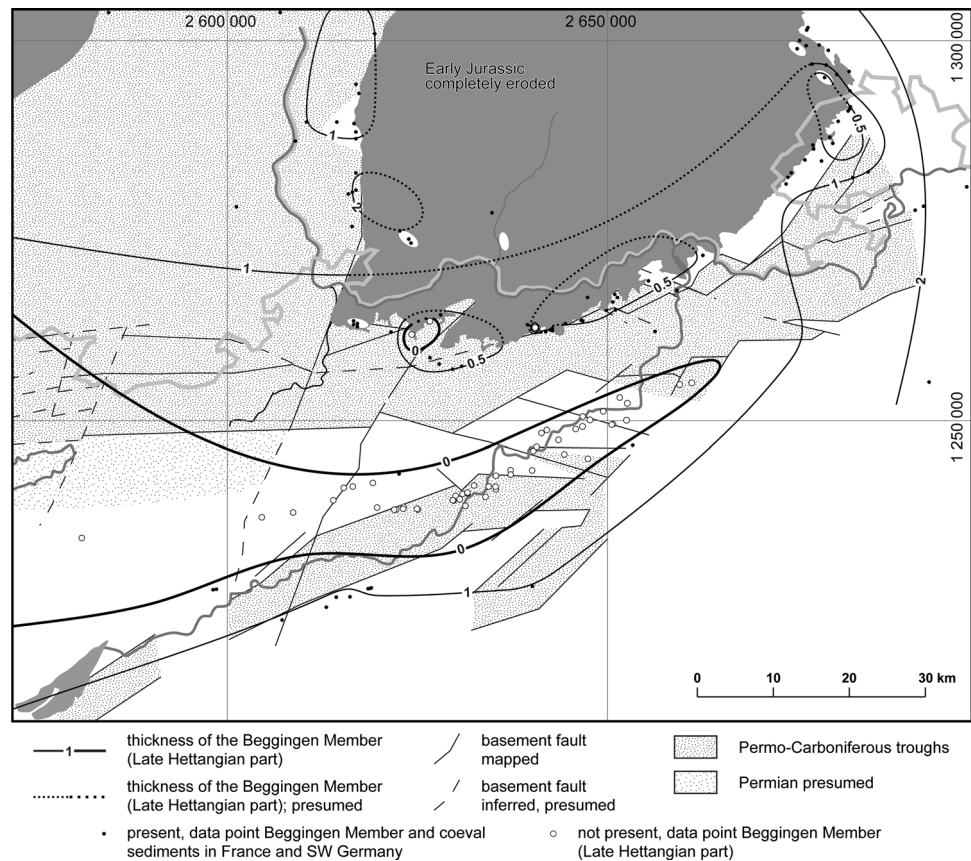
The thickness pattern of the early Pliensbachian shows a subdivision of the study area into two parts. In the W, the deposits are rather thick (> 5 to > 10 m) compared to the E, covering 80% of the area, where they are only up to 3 m thick (Fig. 11). The boundary between both domains roughly follows the eastern boundary of the Upper Rhine Graben. Thicknesses of ~ 10 m occur S of the Upper Rhine Graben (Reisdorf et al. 2011). The predominantly

low thickness in the E shows an overall trend of decreasing thickness from > 3 m in the N to > 1 m in the S. This trend is superimposed by two thickness minima < 1 m, one located W of the Black Forest is directed N–S, while the other one S of the Black Forest is oriented E–W. However, the small thickness does not exclude that the pattern is affected by uncertainties when evaluating lithology and thickness.

4.7 Rickenbach Member and Müsenegg Bed (Late Pliensbachian–earliest Toarcian)

The thickness of Late Pliensbachian–earliest Toarcian deposits decrease from N to S (Fig. 12). A depocenter is present on each side of the Black Forest while the sedimentary cover has been removed by erosion. In the east thickness is significantly smaller (~ 6 to ~ 10 m) than in the west where ~ 6 to ~ 30 m sediments occur in the Upper Rhine Graben. South of these depocenters, thickness decreases with a steep gradient to < 3 m, while further south thickness is < 1 m. Locally, Late Pliensbachian to earliest Toarcian sediments are even absent.

Fig. 8 Palinspastically restored isopach map of the Base Beggingen Member (Staffelegg Formation), Angulatenton Formation, Lumachelle à Angulata; Late Hettangian. Permo-Carboniferous troughs and faults simplified after Wetzel (2008)



4.8 Rietheim Member (early Toarcian)

The isopach map of the early Toarcian is accentuated by two depocenters and two thickness minima (Fig. 13). The depocenters are located E and W of the Black Forest (see above). The eastern maximum is oriented N–S and its thickness varies between 7 and 12 m. The depocenter in the W covers the area of the Upper Rhine Graben, there containing 9–12 m sediments, and continuing to the S to reach a maximum of ~ 19 m.

In contrast, early Toarcian deposits S and E of the Black Forest are thinning from N to S and finally wedge out and hence, constituting an N–S-oriented, large, low-thickness area (< 3 m). Directly W of the Black Forest, a minimum (1.5 to ~ 3 m) occurs on a small area between Ballrechten and Badenweiler; it is N–S oriented and shows a steep thickness gradient.

4.9 Gross Wolf Member of the Staffelegg Formation and basal part of the Opalinus-Ton (Late Toarcian)

Thickness values around < 1 to 3 m widely occur, the lowest values in the S (Fig. 14). However, four depocenters occur, two in the E and two in the W. The eastern ones reach moderate values of ~ 6 m and 8 m, respectively.

The depocenter in the NE (Wutach area) is small and N–S oriented (Fischer 1964). The other one covers a larger area and exhibits an ENE–WSW elongation.

Compared to the remaining part of the study area, the two western depocenters exhibit thicknesses one to two orders of magnitude larger, in the eastern Upper Rhine Graben area up to ~ 39 m (continuing to the N). To the S thickness decreases over a short distance to ~ 5 m. Sediments in the SW of the study area (Mt. Terri area) reach ~ 43 m thickness (cf. Hostettler et al. 2017). South- and eastwards, thickness decreases over short distance according data of Glauser (1936). Towards the N, however, the thickness decreases over a distance of about 40 km to 10 m.

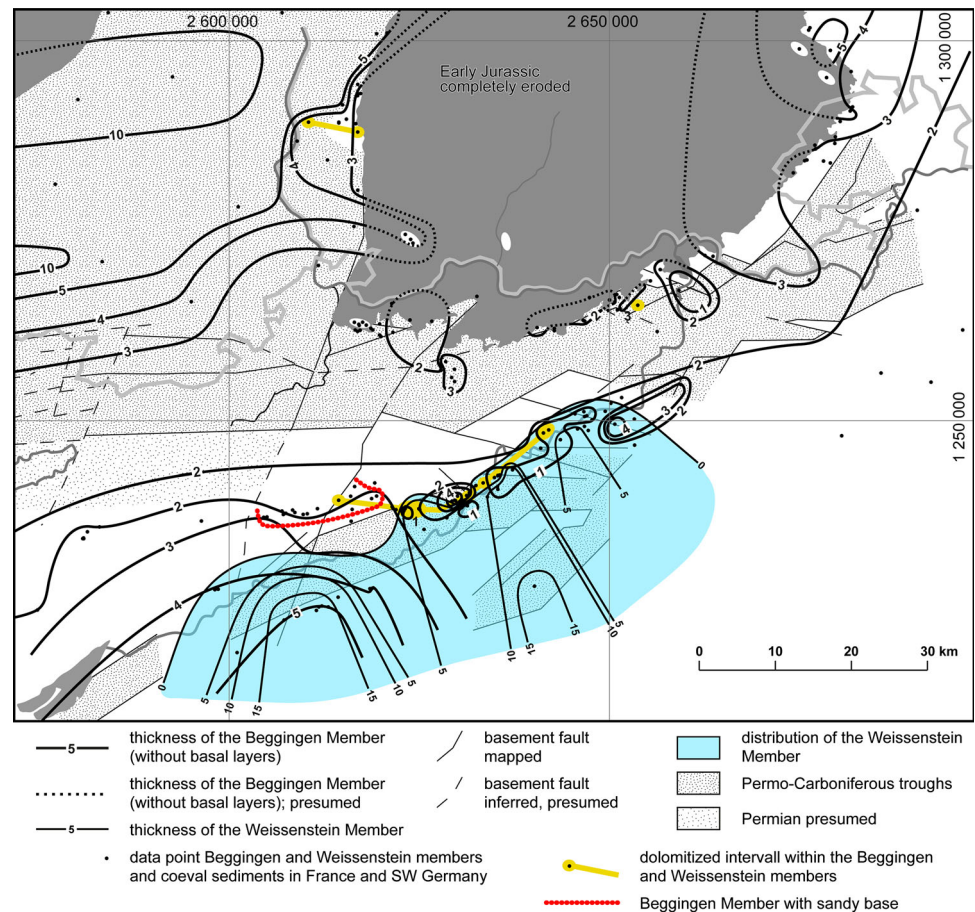
5 Interpretation and discussion

5.1 Bathymetry

5.1.1 Schambelen Member

The Schambelen Member is predominantly composed of marly terrigenous mudstone containing a fully marine fauna (Jordan 1983; Haldimann 2005). The local occurrence and lamination present in some intervals as well as

Fig. 9 Palinspastically restored isopach map of the Beggingen and Weissenstein members (Staffelegg Formation), Arietenkalk Formation, Calcaire à Gryphées; Early Sinemurian–early Late Sinemurian. Permo-Carboniferous troughs and faults simplified after Wetzel (2008)



occasional tempestitic layers implies deposition in an open, but temporarily restricted lagoonal setting not fully connected to the open sea (Wetzel et al. 1993; Meyer and Furrer 1995). A depositional water depth of < 10–15 m is assumed while small areal extent and short fetch restricts the build-up of large storm waves. Coastal sediments of the same age are not present in the study area. The overlying silty to fine sandy bioturbated mudstone and abundant coquinas suggest that these sediments formed around the fair-weather wavebase (~ 10 m).

5.1.2 Beggingen Member

At the base of the Beggingen Member several up to 1.3 m thick reworking horizons are marked by coquinas containing *Cardinia* and/or *Plagiostoma* and occasionally iron ooids (Reisdorf et al. 2011; cf. Seilacher 1982; Einsele 1985). They are interpreted to have formed within the range of fair-weather waves (5–10 m; Fürsich 1995; Wetzel 2000). These open marine deposits may contain fossils reworked from underneath (Reisdorf et al. 2011).

Overlying calcarenites are rich in reworked phosphorized moulds of invertebrates and phosphatic pebbles.

Intercalated are marls with abundant *Gryphaea*, often still in life position, and phosphatic concretions. These deposits likely accumulated both below (marls) and above (arenite) fair-weather wavebase (< 10–15 m; Wetzel 2000). The local occurrence of a thin layer with dolomite at the top of the Beggingen Member (Buser 1952: 62), and other dolomitization phenomena may point to localized short-term emergence (Wetzel et al. 1993; Fig. 9).

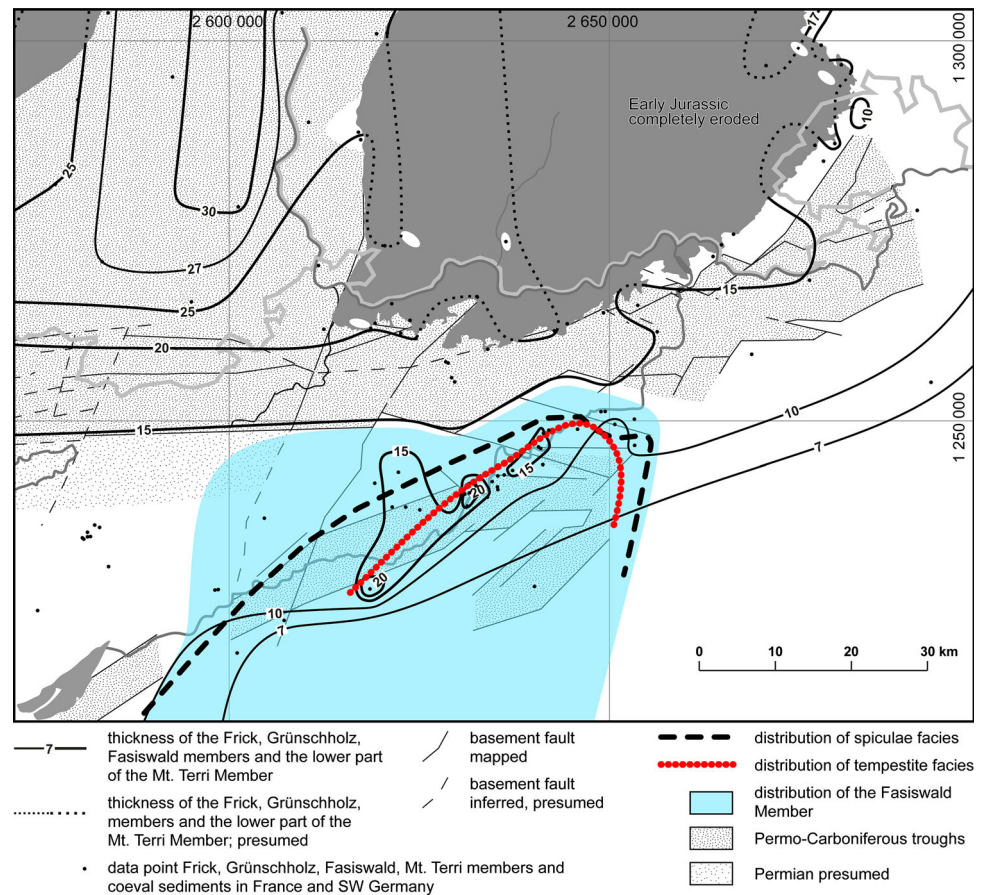
5.1.3 Weissenstein Member

The interfingering of rather clean calcareous sandstones and sandy limestones of the Weissenstein Member with the Beggingen Member within a small area suggests sediment accumulation around fair-weather wavebase (± 10 m). Localized dolomitization in the Weissenstein Member could document short-term emergence or temporary inflow of freshwater (Jordan 1983; Wetzel et al. 1993).

5.1.4 Frick Member

The uniform and locally sandy terrigenous mudstones, rarely exhibit primary sedimentary structures, such as

Fig. 10 Palinspastically restored isopach map of the Frick, Grünschoholz, Fasiswald members and basal part of the Mt. Terri Member as well as the Obtusus Formation and Lotharingien (early Late Sinemurian–Early Pliensbachian). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)



bedding planes or small-scale ripples (NAGRA 1989). Therefore, in analogy to the Opalinus-Ton a depositional water depth at or below storm wavebase or somewhat below is assumed (± 30 m; cf. Wetzel and Allia 2003).

5.1.5 Grünschoholz Member and Fasiswald Member

Conspicuous layers of bioclasts including encrinites and *Gryphaea*-conglomerates are suggestive of a depositional water depth between fair-weather and storm wavebase (10 to < 30 m). Tempestites are restricted to the southern part of the study area (Fig. 10). Similarly, spicules of siliceous sponges within the Fasiswald Member imply a water depth between 15 and 30 m (cf. Brunton and Dixon 1994). Similar faunal content and sedimentary facies of the Grünschoholz Member suggest a similar bathymetry (20 to < 30 m).

5.1.6 Mt. Terri Member

Terrigenous mudstone and marl of this member display characteristics very similar to Frick Member (and tempestites have not been observed; Reisdorf et al. 2011). Consequently, a depositional water depth below storm wavebase (> 30 – 40 m) is assumed.

5.1.7 Breitenmatt Member (including Müsenegg Bed)

The strongly condensed marl intervals and phosphoritic, predominantly concretionary limestones are rich in belemnites and gryphaeid oysters and accumulated around fair-weather wavebase (< 10 – 15 m). Evidence for shallow water depth are reworked belemnites and phosphoritized moulds of invertebrates such as *Gryphaea* as well as phosphatic pebbles (Wetzel et al. 1993; Wetzel and Reisdorf 2007; cf. Sahagian et al. 1996; Arp and Schulbert 2010).

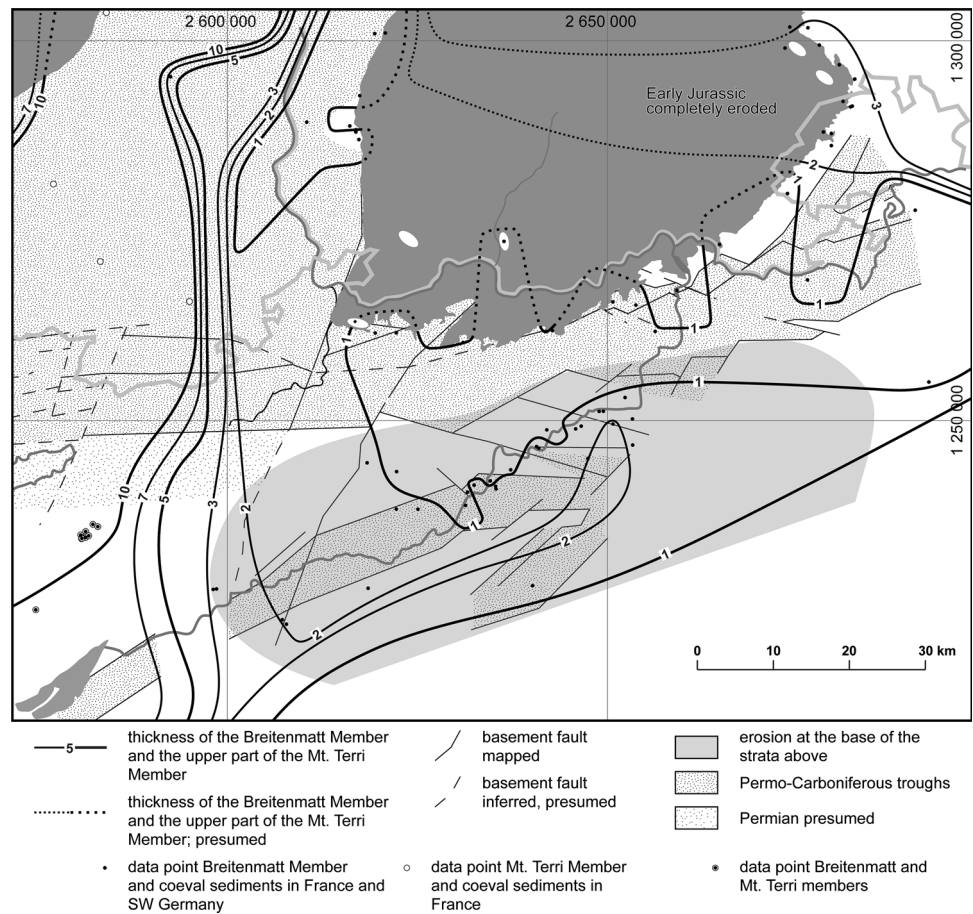
5.1.8 Rickenbach Member

The condensed glauconitic, phosphoritic, highly fossiliferous, belemnite-rich marls are indicators for deposition below fair-weather wavebase, but within the range of storm wavebase (20–30 m; cf. Futterer 1978; Brandt 1985; Doyle and Macdonald 1993).

5.1.9 Rietheim Member

For these bituminous, predominantly thinly bedded terrigenous mud- and siltstones, a depositional water depth of $>$

Fig. 11 Palinspastically restored isopach map of Breitenmatt Member and upper part of the Mt. Terri Member as well as the Numismalismergel Formation and the Carixien (early Pliensbachian). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)



60 m is assumed based on the *post mortem* fate of ichthyosaurs (Reisdorf et al. 2012).

5.1.10 Gross Wolf Member

The Gipf Bed and the Erlimoos Bed representing the basal layers of the Gross Wolf Member rest on an erosional unconformity. Numerous reworking features in combination with iron ooids and/or stromatolites and sponges in these marker beds indicate a depositional water depth around the fair-weather wavebase (5 to > 10 m; cf. Rieber 1973; Böhm and Brachert 1993; Brunton and Dixon 1994). For the grey phosphoritic marl and concretionary marly limestone strata further up a water depth below storm wave base is assumed (Jordan 1983). Tempestites (encrinurites) are known from this member exclusively from the Unterer Hauenstein area (Wetzel, unpubl.). A bathymetry of ~ 30 m is, thus, suggested.

5.1.11 Base of the Opalinus-Ton

Reworking at the base of the Opalinus-Ton is only evident in the southernmost study area (NAGRA 1992).

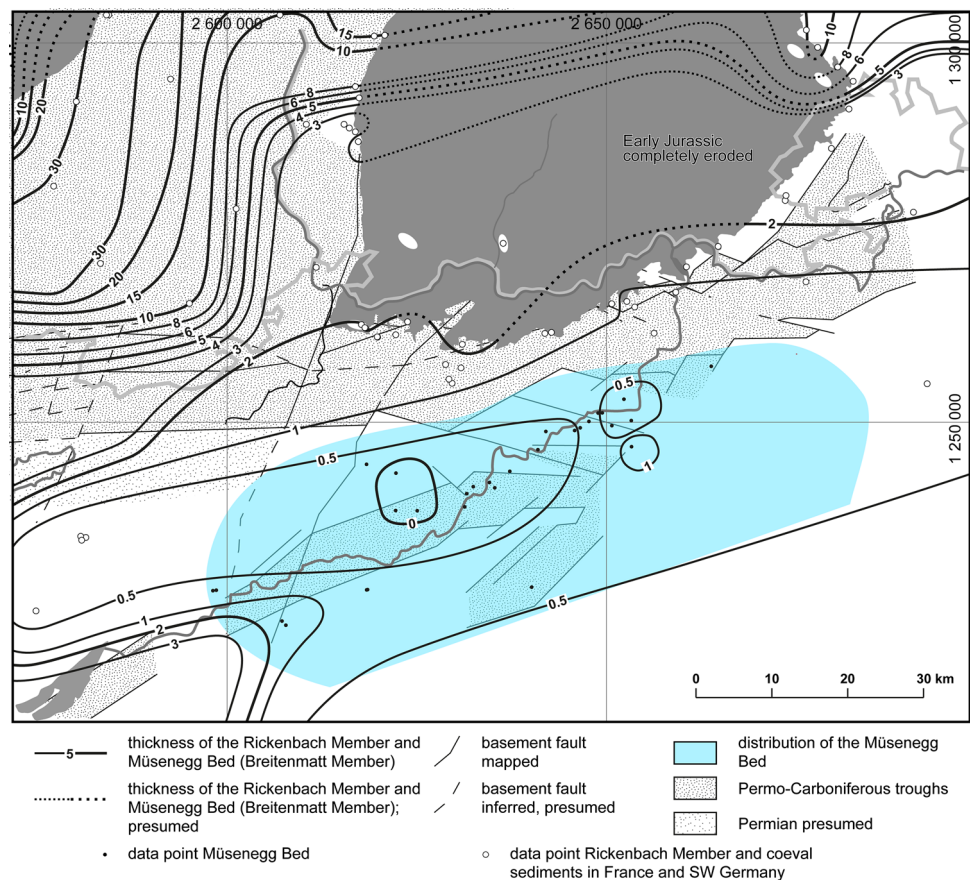
Sedimentological features imply a depositional water depth at or below storm wavebase (± 30 m; Wetzel and Allia 2003). Otherwise for the uniform terrigenous mudstone in NW Switzerland, deposition at or below the storm wavebase in 30–50 m water depth is assumed (Wetzel and Allia 2003).

5.2 Isopach maps

5.2.1 Belchen Member

The facies of the preserved Rhaetian deposits imply a deposition in a brackish-estuarine to shallow-marine setting that was controlled by local topography as indicated by the isopach pattern (cf. Altmann 1965; Geyer et al. 2011; Jordan et al. 2016 and references therein). In the west, the limit of the Belchen Member as well as coeval sediments in France and SW Germany coincide with the Rhenish Lineament and the Wehra–Zeiningen fault zone (Figs. 3, 6). The N–S oriented thickness maximum coincides with the central Upper Rhine Graben and the ENE–WSW trending depocentre between the Rhenish lineament and the Wehra–Zeiningen fault zone implies an alignment with Palaeozoic tectonic structures in

Fig. 12 Palinspastically restored isopach map of the Rickenbach Member and Müsenegg Bed (Breitenmatt Member) as well as the Amaltheenton Formation and Domérien (Late Pliensbachian–earliest Toarcian). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)



the basement that became reactivated. Evidently, not only during the Jurassic (cf., Burkhalter 1996; Wetzel et al. 2003), also pre-Jurassic sedimentation was affected by differential subsidence. Already de Lapparent (1887) and Pfannenstiel (1932) envisaged this possibility, however, for an area a little bit farther N.

5.2.2 Staffelegg Formation

Synsedimentary subsidence during the Early Jurassic has already postulated by Einsele (1985), Wildi et al. (1989), Loup (1992, 1993) and Wetzel et al. (1993, 2003). However, these authors did not address the subsidence pattern and aspects of differential subsidence in detail. In fact isopach maps and spatial distribution of the facies of the various lithologic units imply that the area was affected by differential subsidence that changed with time (see below).

5.2.3 Schambelen Member

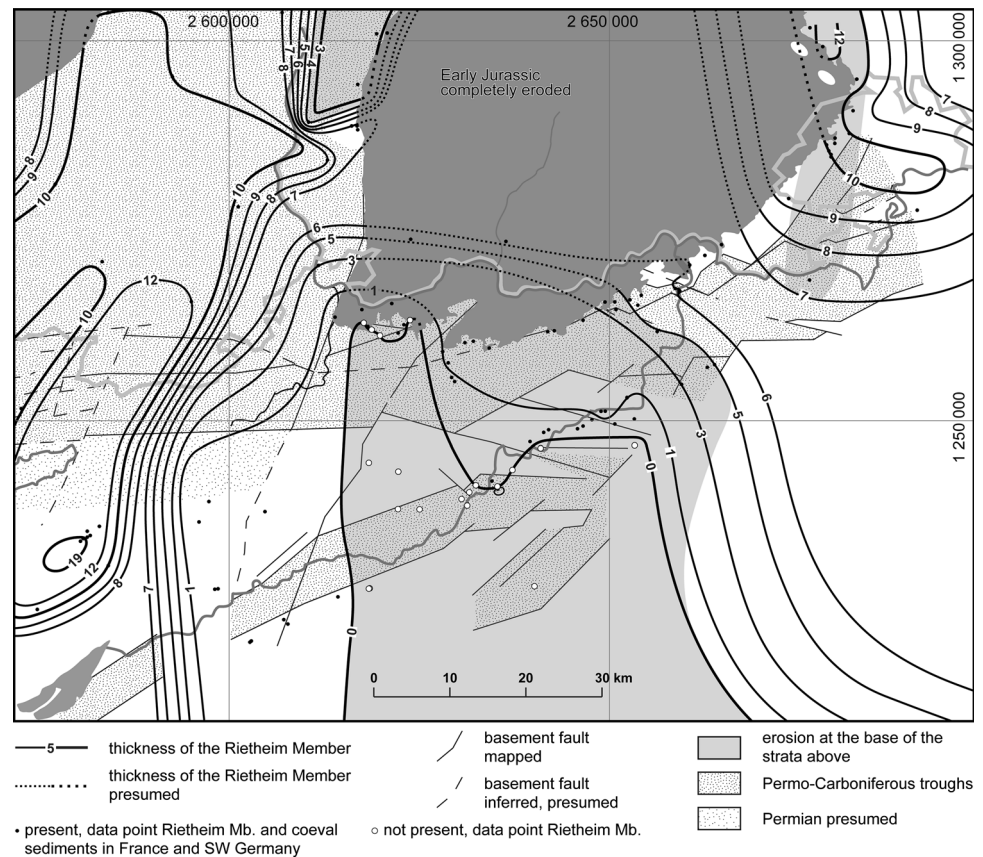
The depocentre between Brugg and Schafisheim (~ 9 m) and that in the Wutach area (~ 9 m) appear of being located along a Rhenish striking axis that crosses two troughs in the basement, the Constance-Frick Trough and the eastern extension of the Olten Trough, and continues

into the so-called “Swabian Depression” of Einsele and Schönenberg (1964; Figs. 3, 7). This axis coincides with faults transecting the graben structures, for instance in the area of Brugg or forming the southern limb of the Olten Trough (Fig. 3). However, in the area of the “Swabian Depression” no tectonic faults are known so far (cf. Murawski 1960; Geyer et al. 2011), but seismic investigations have not been carried out. The “Swabian Depression” strikes NNE–SSW from Stuttgart to Constance and is already documented in the sedimentary record during the Triassic (Einsele and Schönenberg 1964; Krimmel 1980). Therefore, a tectonic origin of this structure is not unlikely.

5.2.4 Beggingen Member

The strongly condensed Late Hettangian sediments at the base (> 0–2 m) display no distinct depocentres (Fig. 8). Still, isopachs of this member reveal an ENE–WSW trend south of the Black Forest that coincides with the strike of the Constance-Frick Trough and the Olten Trough. Further up, the Early Sinemurian to early Late Sinemurian condensed deposits of the Beggingen Member show only weakly developed N–S to E–W trending depocentres (Fig. 9). Thickness differences of > 3 m are indicative of

Fig. 13 Palinspastically restored isopach map of the Rietheim Member, Posidonienschiefer Formation and schistes carton (early Toarcian). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)



enlarged subsidence as seen in the Wutach area for that no Palaeozoic faults are known (see above).

In the Upper Rhine Graben area thickness reaches relative maxima (~ 10 m) being roughly E–W oriented, but they are delimited by the 3-m-isopach having an overall NNE–SSW orientation. In an area between the Rhenish Lineament and the Werra-Zeinger fault zone SW of the Black Forest, the isopach pattern shows a E–W trend and thus, corresponds to that of Permo-Carboniferous faults underneath (cf. McCann et al. 2006).

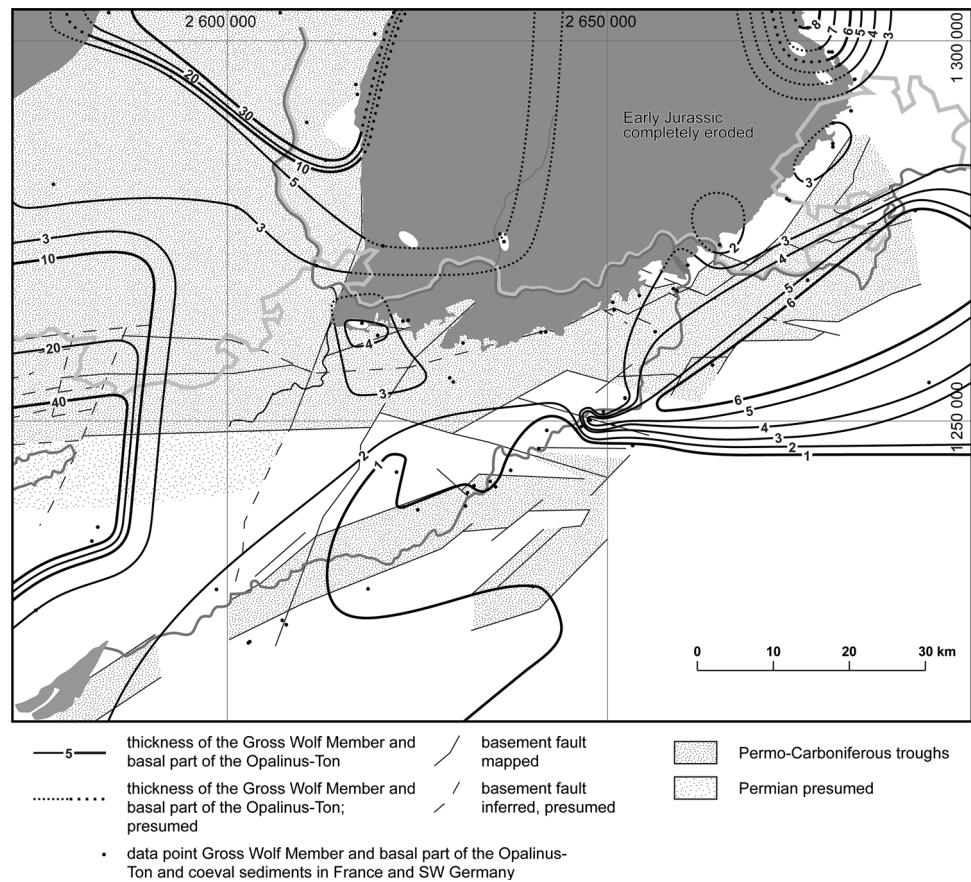
The thickness maximum ~ 5 m of the Beggingen Member in the Weissenstein area occurs above the eastern tip of the southern boundary faults of the Olten Trough (cf. Madritsch et al. 2008). Local occurrences of the Beggingen Member being 3–5 m thick are situated above the Olten Trough and continue along the ENE–WSW striking southern margin of the Constance-Frick Trough. However, while located above several faults, they could have been reactivated simultaneously or subsidence of the Early Jurassic seafloor was affected by Triassic salt underneath (Wetzel et al. 2003).

5.2.5 Weissenstein Member

The S–N- to SSE–NNW oriented tongue-shaped and thinning occurrence of sandy deposits of the Weissenstein Member suggests sediment delivery from the Alemannic Land (Fig. 9; e.g., Trümpy 1980; Wetzel et al. 1993). However, even if sediment input appears to be reflected by this pattern, sediments only become part of the rock record below base level. The northern limit of the Weissenstein Member shows an overall ENE–WSW trend that disappears above the Olten Trough. Thickness up to 22.5 m reflects significant subsidence. Enhanced subsidence at this time is also recorded further to the SW in the well Altishofen (Fischer and Luterbacher 1963; Büchi et al. 1965).

Dolomite-bearing intervals within the Beggingen and Weissenstein members appear along an ENE–WSW direction adjacent to the northern boundary fault of the Olten Trough. Dolomite was encountered where these two lithostratigraphic units show reduced thickness. Dolomitisation very likely resulted from emergence of this area (Wetzel et al. 1993). This constellation is interpreted as evidence for differential subsidence related to a reactivated Paleozoic fault zone.

Fig. 14 Palinspastically restored isopach map of the Gross Wolf Member (Staffelegg Formation) and basal part of the Opalinus-Ton, the Jurensismergel Formation and basal part of the Opalinuston Formation as well as Toarcien marneux and basal part of the marnes à opalinum (Late Toarcian). Permo-Carboniferous troughs and faults simplified after Wetzel (2008)



5.2.6 Frick Member, Grünschoz Member, Fasiswald Member and lower part of the Mt. Terri Member

Subsidence in the Upper Rhine Graben area started to increase during the Early Sinemurian and continued during the Late Sinemurian to Early Pliensbachian, while the area east of the Wehra-Zeiningen fault zone slowly subsided. In the Klettgau area, low thickness (~ 10 m) documents slow subsidence ($\sim \frac{1}{3}$ compared to the adjacent area) close to the boundary of the Constance-Frick Trough (Figs. 3, 10). Only ~ 5 km further S sediment thickness increases above the Constance-Frick Trough to ~ 15 m. As general trend, the Late Sinemurian–Early Pliensbachian strata record higher subsidence above the Constance-Frick Trough than in adjacent areas without Palaeozoic fault systems (cf. Wetzel 2008: Fig. 10.36). This overall trend is also evident above the Olten Trough, where roughly two ENE–WSW trending thickness maxima occur. Therefore, Sinemurian–Early Pliensbachian isopach pattern was modulated by Permo-Carboniferous Troughs as well as the Rhenish Lineament and the Wehra-Zeiningen fault system.

5.2.7 Breitenmatt Member and upper part of the Mt. Terri Member

The subsidence pattern changed significantly during the early Pliensbachian. In the area of the Upper Rhine Graben a domain still shows enhanced subsidence, but the depocentre shifted towards W (Figs. 10, 11). In spite of the westward shift, the NNE–SSW-trend retained. Its western limit extended close to the Rhenish-trending Lubine-Lalaye-Baden–Baden fault zone (Echtler and Chauvet 1992). Thus, subsidence did not accelerate along the Rhenish Lineament and the Wehra-Zeiningen fault zone.

Southward of the Lubine-Lalaye-Baden–Baden fault zone sediment accumulation increased during the early Pliensbachian for the first time within the area of the Upper Rhine Graben and into an area where presumably a continuation of the Permo-Carboniferous trough system is situated (cf. Ustaszewski et al. 2005; Madritsch et al. 2008). In the remaining area, including that above the Constance-Frick and Olten troughs subsidence was slow (Fig. 11).

5.2.8 Rickenbach Member and Müsenegg Bed

During the Late Pliensbachian to earliest Toarcian, the previous subsidence pattern is largely retained. Above the Permo-Carboniferous troughs subsidence is low, while subsidence increased within the central part of the Upper Rhine Graben (Figs. 11, 12). E of the Black Forest a N–S-trending depocentre occurs in the Wutach area.

5.2.9 Rietheim Member

The spatial arrangement of early Toarcian depocentres resembles that of the Pliensbachian in the Wutach and Upper Rhine Graben area, but not outside (Figs. 11, 12, 13). These depocentres are aligned in Rhenish direction. The southward shift of the depocentre in the Upper Rhine Graben towards the Mt. Terri-area marks, however, a considerable change. As during the early Pliensbachian, the area west of the Rhenish Lineament and its southern continuation shows enhanced subsidence (Figs. 11, 13). Late Paleozoic sediments of yet unknown thickness may occur underneath (Figs. 3, 13).

The isopach map also shows two N–S-trending thickness minima (< 3 m). The large minimum extends from the Black Forest towards the south and crosses the Olten Trough and the Constance-Frick Trough. In the north, the narrow minimum runs roughly along the Rhenish Lineament. The sediments show signs of reworking that probably happened during the sea-level low-stand of the Variabilis Zone (Knitter and Ohmert 1983; Einsele 1985; Kuhn and Etter 1994). Therefore, these minima resulted from erosion that occurred at least partly in vicinity to the mentioned tectonic structures (Fig. 13).

5.2.10 Gross Wolf Member and basis of Opalinus-Ton

Areas of high and low subsidence subsisted with some modifications during the Late Toarcian such as depocentres in the Upper Rhine Graben and the Wutach area (Figs. 13, 14). The erosive relief formed during the early Variabilis Zone in the Upper Rhine Graben area was levelled out during the late Variabilis Zone (Knitter and Ohmert 1983; Einsele 1985; Riegraf 1985).

Thereafter, during the Aalensis Zone, subsidence increased significantly in the area around Freiburg and at Mt. Terri (Wetzel and Allia 2003; Reisdorf et al. 2016; Hostettler et al. 2017). Due to missing high resolution biostratigraphic data, it remains unclear whether rather high subsidence prevailed in the area between Mt. Terri and the Upper Rhine Graben or whether two separate depocentres existed, separated by a slowly subsiding domain (as shown in Fig. 14).

Apart from the areas of enhanced subsidence during the Late Toarcian, subsidence increased locally above Permo-Carboniferous fault systems, but in some areas data are too sparse. In the eastern part of the study area increased subsidence resulted in an ENE–WSW isopach trend.

5.3 General aspects of sediment thickness distribution

The lithostratigraphic units shown in the isopach maps formed within a particular, but rather narrow range of depositional water depth, while their facies characteristics and faunal contents are quite uniform for each unit. The individual isopach maps document the effect of the emergent Alemannic Land in the S expressed mainly by the overall southward decreasing thickness. This trend is, however, not exclusively caused by reduced sediment accumulation. In particular, the mudstone-dominated units (Schambelen Member, Frick Member, Fasiswald Member and Rietheim Member) are increasingly erosively truncated towards the south (cf. Riegraf 1985; Brandt 1986; Bloos 1990; Kuhn and Etter 1994). Furthermore, synchronous lithostratigraphic units adjacent and distant to the Alemannic Land differ in facies and infinger, in particular the Sinemurian to Early Pliensbachian lithostratigraphic units (Figs. 9, 10).

Different facies and, thus, lithostratigraphic units formed during the same time (Fig. 5). Synchronous units, however, differ only little, about ± 5 m in their depositional water depth except the Mt. Terri and Breitenmatt Member for which a bathymetric difference of ~ 15 m is estimated. Synchronous units exhibit an overall trend of decreasing thickness southward that is superimposed by positive and negative deviations discussed below.

Except the condensed Pliensbachian strata (Breitenmatt and Rickenbach Member), the thickness of the stratigraphic units of the Staffelegg Formation exceeds the eustatic sea-level rise during the corresponding period (Fig. 5; Table 1). The Pliensbachian strata in SE Germany and E France are even thicker than the concomitant eustatic sea-level rise. Therefore, additional accommodation space must have been provided by subsidence and hence, isopach maps reflect the subsidence pattern.

5.3.1 Early Jurassic transgression surface

The relief of the depositional area at the onset of the Jurassic transgression might have influenced the isopach patterns of the basal Early Jurassic strata. They rest on the Klettgau Formation, in particular the Belchen or the Grulhalde Member (see above; Reisdorf et al. 2011; Jordan et al. 2016). Where the Belchen Member was eroded or did not form, the Klettgau Formation shows reduced thickness (Figs. 6, 7; Jordan et al. 2016). The particular N–S-trending

zone south of the Black Forest has been called “Black Forest-Aar Massif Rise” (e.g., Trümpy 1980; Wetzel et al. 1993; Jordan et al. 2008; Fig. 6). However, the morphology of this domain in Late Rhaetian and Early Jurassic times is not really known (Schneebeli-Hermann et al. 2018; see also Trunkó 1998). Furthermore the reason for missing Rhaetian deposits, non-deposition or later erosion, remains speculative (Altmann 1965; Aepler 1974; Etzold and Schweizer 2005). Similarly, original thickness and amount of erosion of the Belchen Member remains unknown (cf. Etzold and Schweizer 2005; Nitsch et al. 2005).

The western boundaries of the overlying Early Hettangian Schambelen Member and Beggingen Member coincide with the area of reduced thickness of the Klettgau Formation implying the presence of a positive relief (Fig. 7; Jordan et al. 2016). Similarly, the thickness of the Schambelen Member decreases eastward where the thickness of the Klettgau Formation increases. In contrast, the two depocentres of the Schambelen Member are located where no Rhaetian sediments are present (any longer) and the Klettgau Formation exhibits the lowest thickness (> 20 to 40 m). This pattern suggests that a negative relief became filled suggestive of relief inversion. However, the Schambelen Member accumulated in rather uniform water depths of 5–10 m and, therefore, at the onset of the Early Jurassic transgression very likely a low-relief coastal plain was flooded. Because of the fine-grained nature of both Belchen and Schambelen Member, layers consisting of reworked material are highly unlikely to occur. However, considering the mentioned topography of the boundary between both members, erosion occurred in the time span between Belchen and Schambelen Member or when the Schambelen Member started to form (Figs. 5, 7; Reisdorf et al. 2011; Schneebeli-Hermann et al. 2018). In contrast, the Beggingen Member that accumulated in < 10–15 m water depth commonly exhibits reworked material at the base and hence, documents erosion of the substrate.

5.3.2 Transgression direction of the Jurassic Sea

The direction of Jurassic transgression is recorded by the oldest Jurassic sediments preserved in NW Switzerland, E France and SW Germany (see Debrand-Passard 1980, 1984a, b; Mégnien and Mégnien 1980; Wetzel et al. 1993; Geyer et al. 2011). The earliest Early Jurassic sediments are reported from Kleiner Heuberg near Balingen (SW Germany, ~ 50 km N of Switzerland; earliest Planorbis zone; Altmann 1965; Bloos 1999; Bloos and Page 2000). Slightly younger sediments of the Planorbis zone occur somewhat to the SW (Altmann 1965; Krimmel 1980; Schlatter 1983) and continue to the S to NW Switzerland (Hallau Bed of the Schambelen Member; Planorbis zone; Fig. 5; Schlatter 1983; Reisdorf et al.

2011). Therefore, transgression of the Jurassic Sea in the study area was SW-directed (see Wetzel et al. 1993; Geyer et al. 2011).

5.4 Isopach pattern, basement structures and stress field

The isopach patterns of the studied strata shows recurrently conspicuous spatial relation to Paleozoic fault systems in the basement. Relative isopach minima and maxima are superimposed on a general trend of southward decreasing thickness. Pronounced depocentres and areas of reduced thickness showing these Palaeozoic preferential strike directions, however, indicate that in many instances only parts of the Palaeozoic faults became reactivated (see above).

The recurrently preferred orientations of isopach anomalies suggest causal relationship to the tectonic stress field during the Early Jurassic that was characterized by a NW–SE extensional regime while rifting affected the Tethyan and the North Atlantic realm (Ziegler 1990; Philippe et al. 1996; Scheck-Wenderoth et al. 2008). This extensional regime has had the potential to reactivate at least parts of the Palaeozoic tectonic structures forming part of the Rhenish Lineament, the Wehra-Zeiningen fault zone and the Permo-Carboniferous trough system.

All these faults appear to have dissected the basement into a block-mosaic (Diebold and Naef 1990). Differential movements between individual blocks very likely occurred during strike-slip movements in the mentioned stress regime (see Reicherter and Reinecker 2008; Lenoir et al. 2014). For instance, conjugate fault systems may result in small-scale pull-apart basins parallel to trough axis and induce small-scale subsidence domains as recorded by the Early Sinemurian strata in NW Switzerland (Figs. 3, 9). Differential subsidence within the basement related to block rotation or strike-slip movements, however, are very likely transformed into flexural movement on the seafloor while affected by ductile deforming Triassic salt (e.g., Wetzel et al. 2003).

The patterns of the individual isopach maps imply a slight change of the stress field during the Early Jurassic. For instance, the youngest Sinemurian sediments in the area of the Upper Rhine Graben show an increase in thickness towards W that is superimposed on the above mentioned N–S trend (see above, Fig. 10). Since the late Sinemurian N–S-trending, large-scale depocentres prevail along the Rhenish Lineament and similarly oriented faults. However, the depocentres repeatedly shifted towards or away from the center of the Upper Rhine Graben (Figs. 7, 8, 9, 10, 11, 12, 13, 14), but also beyond its borders to the S to the Mt. Terri area. The depocentre located in the southern extension of the Upper Rhine Graben between the

Rhenish Lineament and Caquerelle Fault implies a southward continuation of the Burgundy Trough extending beyond its known boundaries (Figs. 3, 11, 13, 14). A similar result was obtained for the Late Oxfordian to Late Kimmeridgian Reuchenette Formation (Jank et al. 2006; Fig. 17).

The isopach patterns of Early Jurassic strata can be interpreted as the result of a sequential brittle reactivation of faults dissecting the basement. This also applies to significant thickness minima that are located in the area of the Upper Rhine Graben (Figs. 11, 13). In particular, in the Courtemaury section in the Mt. Terri area a hiatus comprises the period from the latest Early Sinemurian to the early Pliensbachian (Turneri to Ibex zone) due to erosion (Reisdorf et al. 2011), while in sections in ~ 500 m distance during this period ~ 10 m thick sediments accumulated (e.g., section Les Salins; see Reisdorf et al. 2011).

5.5 Thermal effects of extension

Effects of approximate NW–SE extensional stresses increased at the beginning of the Middle Jurassic and continued at varying intensity until the Late Jurassic causing considerable differential subsidence in relation to Palaeozoic faults in the basement (Philippe et al. 1996; Wetzel et al. 2003). Many of these deposits are characterized by significant facies changes and large thickness (Wetzel et al. 2003). Furthermore, lithospheric extension during the Late Triassic and Early Jurassic led to heating of the basement and subsequent thermal subsidence (Timar-Geng et al. 2004; Scheck-Wenderoth et al. 2008). In addition, extensional stresses resulted in hydrothermal activity recorded by vein mineralizations and mineral alterations. Many veins outcropping or drilled in the Vosges and Black Forest area were chronometrically dated. They reveal a Rhaetian to Early Jurassic age. However, the age spectra are often wide and, therefore, they cannot be ascribed to distinct pulses of fault reactivation (Wetzel et al. 2003 and references therein; Timar-Geng et al. 2004; Baatartsogt et al. 2007; Edel et al. 2007).

For some of the dated veins, the orientation is documented having E–W to WNW–ESE strike directions in the southern Black Forest (Werner et al. 2002), as well as NW–SE in the central Black Forest (Bonhomme et al. 1983; Werner et al. 2002). These data support that Palaeozoic fault systems in the basement of NW Switzerland and adjacent areas became reactivated during the Jurassic. Chronometric age data giving a narrow spectrum document hydrothermal activity during the Rhaetian in the Black Forest (Wernicke and Lippolt 1995; Staude et al. 2012), and during the Hettangian (Wernicke and Lippolt 1995; Brander 2000), Sinemurian (Werner et al. 2002), Pliensbachian (Lippolt

et al. 1986; Werner et al. 2002) as well as during the Toarcian (Mertz et al. 1991; Wernicke and Lippolt 1994; Pfaff et al. 2009). In particular fault systems became reactivated that are oriented similar to the North-Swiss Permo-Carboniferous Trough.

6 Summary and conclusions

For sediment successions of considerable thickness in epicontinental basins, the effects of synsedimentary tectonic movements have been recurrently demonstrated, while rather thin deposits were subordinately studied. The Early Jurassic strata in NW Switzerland are rather thin, commonly < 50 m and accumulated in shallow water < 50–60 m deep, but nonetheless the influence of synsedimentary differential subsidence can deciphered by using isopach maps covering time spans of < 6 Myr.

The Palaeozoic basement has been structured at the end of the Variscan orogeny by faults systems being mainly NNE–SSW and NW–SE oriented. They dissect the basement resulting in a mosaic of blocks. Therefore, in response to the stress field small-scale tectonic movements may take place along such fault systems, in particular in an extensional stress field, for instance during the Jurassic, when the Tethys and the North Atlantic Ocean opened. The reactivation of these Palaeozoic fault systems since the Latest Triassic is documented by Rhaetian and Early Jurassic strata that exhibit a variable and complex lithostratigraphic architecture and distinct thickness changes. Because of the in-average low sedimentation rate these changes are often of low magnitude. In many instances, facies and isopach pattern spatially coincide with faults in the basement. The spatial relationships suggest that movements within the basement affected the seafloor above. However, ductile deformation of Triassic salt very likely led to flexural deformation of the Early Jurassic seafloor.

In NW Switzerland and adjacent areas, synsedimentary tectonic activity is particularly obvious in vicinity to the Rhenish Lineament. Displacement along normal faults provided accommodation space for comparatively thick deposits since the Sinemurian. Furthermore, reactivation of faults belonging to the North-Swiss Permo-Carboniferous Trough system is expressed by isopachs displaying a roughly ENE–WSW trend. The individual segments, Constance-Frick Trough, Olten Trough and Klettgau Trough, are reflected in case of activity by isopach patterns at a stratigraphic resolution of a sub-stage. Small-scale isopach anomalies occur above the trough axis. They are suggestive of strike-slip movements along the complex fault systems within the basement.

Chronometric age data of hydrothermal veins and mineral alterations within the basement as well as in the Mesozoic sediment cover document tectonic movements during the Early Jurassic and, hence, support the above sedimentological indications of synsedimentary tectonics.

Isopach maps are not only suitable for the detection of synsedimentary tectonics, but they are also an effective tool to indicate and localise activity of fault systems. Even if the tectonic movements are small during the Early Jurassic. This period should no longer be considered as a time of “tectonic quiescence” in NW Switzerland, E France and SW Germany.

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Summary

The shallow marine Early Jurassic strata found in NW Switzerland and adjacent regions of SW Germany and E France are suitable for the study of eustatic sea level fluctuations as well as for the detection of differential subsidence. These more or less strongly condensed sediments were deposited during ~ 27 Myr in the transitional area between the Swabian Basin and Paris Basin. The analysed sediments are organized in a complex lithostratigraphic architecture, which is characterised by narrow, abrupt variations in facies and thickness.

Based on revised, existing and new litho- and biostratigraphic data, a formal mapping unit is defined for the Early Jurassic deposits of NW Switzerland, the "Staffelegg-Formation". It is subdivided in 11 members and 9 beds. Several of these beds are important correlation horizons in terms of allostratigraphy. Some of them correspond to beds or erosion unconformities encountered in the Swabian Basin, others with strata in the Parisian Basin.

The subsidence was low in the study area during the Early Jurassic. Therefore, sea-level fluctuations in deposition area had a major influence on the accommodation space. The depositional water depth was quantified by classical considerations based on the analysis of lithofacies. Furthermore, vertebrate fossils were used to quantify the depositional water depth. As a result of the taphonomic case study, newly constructed "Ichthyosaur Corpse Curves" for England, SW Germany and NW Switzerland correlate well with the global sea-level curve of the Early Jurassic by Hallam. Therefore, the analysis of differently preserved vertebrate remains (disarticulated vertebrate skeletons or isolated bones) has some potential to serve as a proxy for water depth.

The Early Jurassic time period coincides with the disintegration of Pangea. The sedimentological case study demonstrates that large-scale plate-tectonic processes can be significantly expressed in tectonically supposedly inactive intracontinental basins due to smaller-scale synsedimentary-tectonic activity. Synsedimentary-tectonic activity is already evident in the study area with a chronostratigraphic resolution accuracy of one sub-stage. It manifests itself in an abrupt onset of (i) individual lithostratigraphic units, (ii) facies boundaries, (iii) interfingering of different facies, (iv) erosive truncations, and (v) in more or less significant thickness variations that are localised above Paleozoic fault systems in the basement.

Due to synsedimentary-tectonic activity, additional accommodation space was created. This occurred above ENE-WSW-trending Permocarboniferous troughs (Burgundy Trough, North-Swiss Permocarboniferous Trough) and roughly N-S-trending faults and fault zones (Rhenish Lineament, Wehra-Zeiningen fault zone). The latter established the largest depocenters in terms of area, which also have the greatest thickness for the most Early Jurassic lithostratigraphic units. During this period, the prevailing NW-SE extensional palaeo-stress field resulted in a displacement along reactivated N-S-trending faults as well as in the revival of strike-slip fault systems of the Permocarboniferous troughs. Reactivation of faults in the basement during the Early Jurassic is also evidenced by temporally enhanced hydrothermal activity as documented by chronometric age of veins and mineral alterations in the Black Forest and Vosges.

Curriculum Vitae

Name: Reisdorf
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Higher education

10/92 – 08/98
Degree: Geology Diploma
Studies at the Institute of Geology and Paleontology of the University of Tübingen
Diploma thesis entitled:
“Diagenesis of Orthocerate Limestone by Rich Tamirant, Ludlow, Amessoui Syncline, Morocco”
Diploma mapping entitled:
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Engineering degree

08/89 – 09/92
Degree: Geological engineer
Studies at the Bergakademie Freiberg/Saxony
Specialisation: exploration geology
Thesis entitled:
“Methodical Investigations for the Surveying of Contaminated Sites in the BIUG Engineering Firm”

Technician training

07/84 – 07/86
Degree: Geological technician
Apprenticeship at the “Martin Hoop” school in Johannegeorgenstadt & VEB Geological Research and Surveying Freiberg/Saxony
Specialisation: Solid minerals
Thesis entitled:
“Evaluation of Shallow Boreholes for the Surveying of Tin-Greisen Deposits in the Altenberg Area (Ore Mountains)”

Secondary education

06/74 – 06/84
Polytechnic Secondary School “C.G. Rochlitzer” in Freiberg/Saxony

Practical employment

08/19 – present
Curator Natural Science Collections Ruhr Museum Foundation; Essen

08/18 – 07/19
Deputy Head of Natural Science Collections at the Ruhr Museum Foundation; Essen

02/18 – 07/18
Lecturer at the Department of Environmental Sciences, Research Group Geology-Palaeontology of the University of Basel

06/11 – 12/17	Researcher at the Department of Environmental Sciences (Sedimentology Research Group) at the University of Basel
12/98 – 12/17	Assistant at the Department of Environmental Sciences (Sedimentology Research Group) at the University of Basel
03/11 – 11/17	Reviewer for manuscripts submitted for publication in geological and paleontological journals
06/16 – 07/16	Petrographic study for the Münsterbauhütte Basel
01/12 – 06/16	Palaeontology Collection Assistant at the Natural History Museum of the Burgergemeinde Bern
11/12 – 06/16	Bio- and lithostratigraphic study of the Mt. Terri area (Cooperation with Natural History Museum of the Burgergemeinde Bern/ Nagra/ Swisstopo)
08/15 – 08/16	Svalbard excavation, sedimentological and taphonomic studies; Supervision of five MSc students
08/14 – 11/17	Scientific direction of the touring exhibition “Rock Fossils” (Natural History Museum Bern, Werkforum Dotternhausen, Museum of Natural History Chemnitz, Geomuseum Faxe)
08/13 – 10/13	Fasiswald excavation, scientific direction
12/12 – 02/13	Creation of database entries for the Swiss Committee for Stratigraphy (Lithostratigraphic Lexicon of Switzerland)
10/09 – 10/10	Participation in the multimedia presentation of the Museum of Natural History Olten on the Hauenstein ichthyosaur find (texts, scientific consulting)
02/10 – 03/10	Relocation of the geological collection pieces of the Museum of Natural History Olten (in collaboration with Dr. P. Flückiger and B. Imhof)
08/07 – 09/07	Organisation and direction of the excursion “Lithostratigraphic units proposed to the ‘Swiss Committee for Stratigraphy’ in the context of the revision of the northern Switzerland Lower Jurassic (‘Liassic’); 10-11 September 2007” (in collaboration with Dr. W. Heckendorn and Prof. A. Wetzel)
05/07 – 07/07	Development of the relocation plan for the natural history collection pieces of the Museum of Natural History Olten, including inventory taking (in collaboration with Dr. P. Flückiger and B. Imhof)
01/03 – 10/05	Student Assistant at the Kantonsgeologie Basel-Stadt
09/00 – 11/00	Paleontological and geological consulting for the TRG transit route 3

01/93 – 11/98	Student Assistant: <ul style="list-style-type: none"> • at UMT Umwelt- und Messtechnik Ingenieurgesellschaft mbH Stuttgart • at the Institute of Geology and Paleontology of the University of Tübingen • at the Glatte Bohr GmbH & Co. KG Oberschöna • at the ENMOTEC Geologisches Büro für Erkundung u. Umweltschutz GmbH Tübingen
02/91 – 09/92	Student Assistant at BIUG Umwelttechnik und Grundbau GmbH Freiberg/Saxony
08/86 – 09/86	Temporary employee at the VEB Geologische Forschung und Erkundung Freiberg/Saxony

Courses / Conferences / Lectures

06/00 – 11/17	Various international conferences and workshops
04/04 – 05/16	Various invited lectures
07/16	Collaboration at UniKidsCamp (University of Basel)
04/12 – 11/16	Science Slam lectures in Germany and Switzerland
06/04 – 12/15	Various invited popular science lectures
05/14	Internal workshop “Fellow me! (The Mobile Academy for the International Museum Programme Fellowship)” of the Federal Cultural Foundation on “Mixed Media Design” as well as moderation of the “Fellow Pitch” in Halle an der Saale
10/14	Science Outreach Symposium, Natural History Museum Oslo

Stays abroad

02 – 04/95 and 03/96	Scientific fieldwork for the preparation of a geological map and for sampling in Morocco (diploma thesis)
09/84 – 08/16	Participation in various scientific excursions, mapping courses and excavations in Switzerland, Norway (Svalbard), Germany, Morocco, Iceland, France, Spain and Italy

Awards

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